

Evaluation of the Airport Target IDentification System (ATIDS) Beacon Multilateration System (93-CRDA-0052)

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16. Abstract The Airport Target IDentification System (ATIDS) is a new surveillance and identification system for locating Mode Select Beacon System (Mode S) equipped aircraft and vehicles. Its primary use is as a surface Beacon surveillance system to provide Flight Number Identification (ID) to the existing Airport Surface Detection Equipment Model 3 (ASDE-3) radar and Airport Movement Area Safety System (AMASS). The system is also capable of locating and identifying aircraft in flight or on the ground, which permits the use of the ATIDS system for Parallel Runway Monitor (PRM) and other airborne and surface surveillance applications. ATIDS is compatible with Mode S Automatic Dependent Surveillance (Mode S ADS-B), and can display the location and ID of properly equipped aircraft. ATIDS consists of three or more Receiver/Transmitters (R/Ts) encircling a predetermined coverage area. The system operates by receiving and time stamping the Mode S squitter from a target at three or more R/Ts; transmitting the squitter ID and time stamp to a central computer; measuring the Time Difference of Arrival (TDOA) of the squitter from each time stamp; and calculating the target's position by hyperbolic multilateration. The ATIDS system was evaluated using Federal Aviation Administration (FAA) test aircraft equipped with standard Mode S transponders. Surface accuracy performance was tested first at the Atlantic City International Airport (ACY) and then at the Atlanta Hartsfield International Airport (ATL), and was found to be adequate for the ASDE-3 labeling application, with a Root Mean Square (RMS) error of better than 37 feet. Airborne accuracy performance was evaluated at the ATL and found to be as accurate as the current Electronically Scanned (E-Scan) PRM for ranges greater than 7.24 miles, with an RMS error of better than 44 feet.			
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EXECUTIVE SUMMARY

This report details a candidate system for the Airport Target Identification System (ATIDS). This system enhances safety and efficiency on the airport surface by providing the identity of aircraft, which is currently unavailable to tower controllers. The system can also be adapted to act as a lower-cost alternative sensor for the existing Parallel Runway Monitor (PRM) system. This report provides the results of tests performed on the Beacon Multilateration Surveillance System developed by Cardion, Inc., under the name Cooperative Area Precision Tracking System (CAPTS) which was developed and tested under a Cooperative Research and Development Agreement (CRDA). Cardion, which was a division of the Siemens Company at the time of the CRDA and is now a division of AirSys ATM, was the Cooperative Research Organization (CRO). CAPTS provides a means for locating and identifying aircraft and properly equipped vehicles within a predetermined coverage area.

Multilateration (also known as Time Difference of Arrival or Inverse Loran) is the process whereby a discrete signal from a target is received at various locations surrounding the target, and by knowing the relative position of the receivers and the time difference between reception at the receivers, the target's position can be calculated. The discrete signal used by this system is the Mode Select Beacon System (Mode S) squitter, which is emitted by Mode S transponders.

Testing was performed at the Atlantic City International Airport (ACY) from November 30, 1994 to December 1, 1994, at Atlanta Hartsfield International Airport (ATL) from January 16, 1996, to January 18, 1996, and at ATL from January 10, 1997, to February 5, 1997. Data was collected to measure the two dimensional positional accuracy of the Beacon multilateration concept. The CAPTS system was only being evaluated to prove the multilateration concept, so while the system was generally stable and reliable, specific testing was not conducted at the subsystem, equipment, or interface levels.

This ATIDS candidate Beacon Multilateration System was found to have the following positional accuracies:

<u>Location/Test Type</u>	<u># of Samples</u>	<u>Mean Error</u>	<u>RMS Error</u>	<u>Stan. Dev.</u>	<u>Worst Case</u>
ACY Static Testing CAPTS vs. Laser Tracker	2469	23.41 feet	27.01 feet	13.48 feet	92 feet
ATL Ground Taxi CAPTS vs. Diff. GPS	1623	29.48 feet	36.10 feet	20.85 feet	184 feet
ATL PRM Approaches CAPTS vs. Diff. GPS	4159	31.88 feet	43.93 feet	22.79 feet	641 feet
ATL Coverage Flights CAPTS vs. Diff. GPS	11471	47.37 feet	111.45 feet	33.65 feet	6707 feet

The system has sufficient accuracy on the surface for use as an Airport Surface Detection Equipment Model 3 (ASDE-3) labeling system or for other surface and airborne Mode S surveillance applications in its current form. It is required that data be tracked over several seconds to smooth the periodic >50-foot errors. These errors are caused by garbling or blockage of direct path squit causing a receiver to utilize a reflected path squit. This is statistically unavoidable, but the effects can be reduced through tracker smoothing and better cross-checking of all available solutions. Additionally, a change will be required in the pilot procedures for transponder operation during taxi. The system does not effectively track Air Traffic Control Radar Beacon System (ATCRBS) targets in its current form, but development in that area continues.

1. OBJECTIVES.

This report presents the results of testing done to determine the suitability of Beacon Mutilation as implemented in the Cardion Cooperative Area Precision Tracking System (CAPTS) for uses in Federal Aviation Administration (FAA) Air Traffic Control (ATC). The system was evaluated in two areas; (1) as an Airport Surface Surveillance and Identification sensor, and (2) as an Airborne Beacon Surveillance sensor. In the surface role, the system was configured to demonstrate how it could enhance the Airport Surface Detection Equipment Model 3 (ASDE-3) radar and Airport Movement Area Safety System (AMASS). The ASDE-3 radar is currently installed at major United States (US) airports and while it provides highly accurate target location, it lacks the ability to identify aircraft. The AMASS system is currently undergoing installation at ASDE-3 equipped airports. In the airborne role, the system was configured to demonstrate how it could be used as a low cost alternative to the existing Electronically Scanned (E-Scan) sensor portion of the Parallel Runway Monitor (PRM) system. The PRM is currently undergoing installation and commissioning at five US airports which have closely spaced parallel runways. The system provides high accuracy, high update rate tracking of aircraft, and alerts controllers in the event of conflicts.

2. BACKGROUND.

Airport surface surveillance currently consists of visual surveillance which is augmented by the use of the ASDE-3 Radar System at major US airports. The ASDE-3 provides a high resolution map of the airport with aircraft, airport vehicles, and other targets represented by a video representation of the raw radar return (i.e., skin paint) as shown in figure 2-1. Currently, no identification information is available for targets on the ASDE-3 display.

The AMASS is a new system being developed to enhance the ASDE-3. AMASS tracks ASDE-3 targets, overlays symbology on the ASDE-3 display, and provides safety alerts to controllers. AMASS also provides full Flight Number Identification (ID) for arriving aircraft. No ID is available for departing aircraft. The arriving aircraft is tracked by the Airport Surveillance Radar (ASR) while airborne and uses the target's beacon code to correlate a flight number ID. The aircraft is tracked by the ASDE-3/AMASS after landing while taxiing to the gate. The ASDE-3/AMASS cannot interrogate aircraft transponders and therefore cannot provide ID.

As an aircraft lands, it leaves the coverage area of the ASR and enters the coverage area of the ASDE-3. AMASS transfers the ID from the ASR track to the first ASDE-3 target which appears on the approach runway. This ID then travels with the corresponding AMASS track. It is not possible for AMASS to independently update the validity of this ID. It is possible to transfer the ID to an incorrect AMASS track, drop the ID if the AMASS track is dropped, or swap IDs between two AMASS tracks in close proximity.

AMASS does provide for external interfaces which will permit straightforward fusion of CAPTS information with the AMASS tracks, providing stable verifiable ID on the AMASS ground tracks.

In the FAA's terminal and enroute ATC, surveillance and identification of aircraft is currently implemented in three distinct parts. A Primary Radar, such as the ASR-9 or Air Route Surveillance Radar Model 4 (ARSR-4), provides noncooperative surveillance of all aircraft within a search volume. A Secondary Radar, such as the Air Traffic Control Beacon Interrogator Model 5 (ATCBI-5) or the Mode Select Beacon System (Mode S), is used to provide cooperative identification of all aircraft with operating transponders within a search volume. A Tracking and Display System, such as the Automated Radar Tracking System (ARTS) or the Enroute Automated Radar Tracking System (EARTS) provides tracked data to the controller showing target speed and direction. Also, because of links to ID, the transponder code is converted to an ID which the air traffic controller uses in voice communications with the aircraft.

In Surface ATC, the ASDE-3/AMASS can perform all of the Primary Radar and Tracking Display Functions, but conventional Secondary Radar are not applicable to Airport Surface Operations. Conventional Secondary Radar Antennas are installed atop the rotating Primary Radar Antenna and operate by emitting a series of interrogation pulses. This causes the aircraft's transponder to emit a series of reply pulses which contains the aircraft's ID. This ID is assigned by the air traffic controller and is set by the pilot prior to departure.



FIGURE 2-1. ASDE-3 DISPLAY - ATLANTA

In primary radar, a pulse of Radio Frequency (RF) energy reflects off of the metal surface of the aircraft. The reflection of the RF is instantaneous, allowing an accurate calculation of the distance between the radar and aircraft. In secondary radars (also known as Beacon systems), a transponder on the aircraft must receive, decode, and reply to the interrogation sent by the radar. A variety of factors effect the range accuracy of transponders. Transponders are considered to be accurate in range to 500 feet, and while this is sufficient for airborne use, a variety of factors make standard interrogation methods impractical on the airport surface.

Consider a line of aircraft on a taxiway preparing to depart. Even two of the largest aircraft would be closer than 500 feet apart while taxiing. If the aircraft were aligned along a radial of the interrogator, as shown in figure 2-2, a single interrogation pulse would cause all of the aircraft to emit replies spaced very closely in time. There would be a very high probability that these replies could interact, a phenomena known as garbling, making decoding impossible. Buildings, other structures, and even the runway surface can reflect the replies causing multipath and synchronous garble.

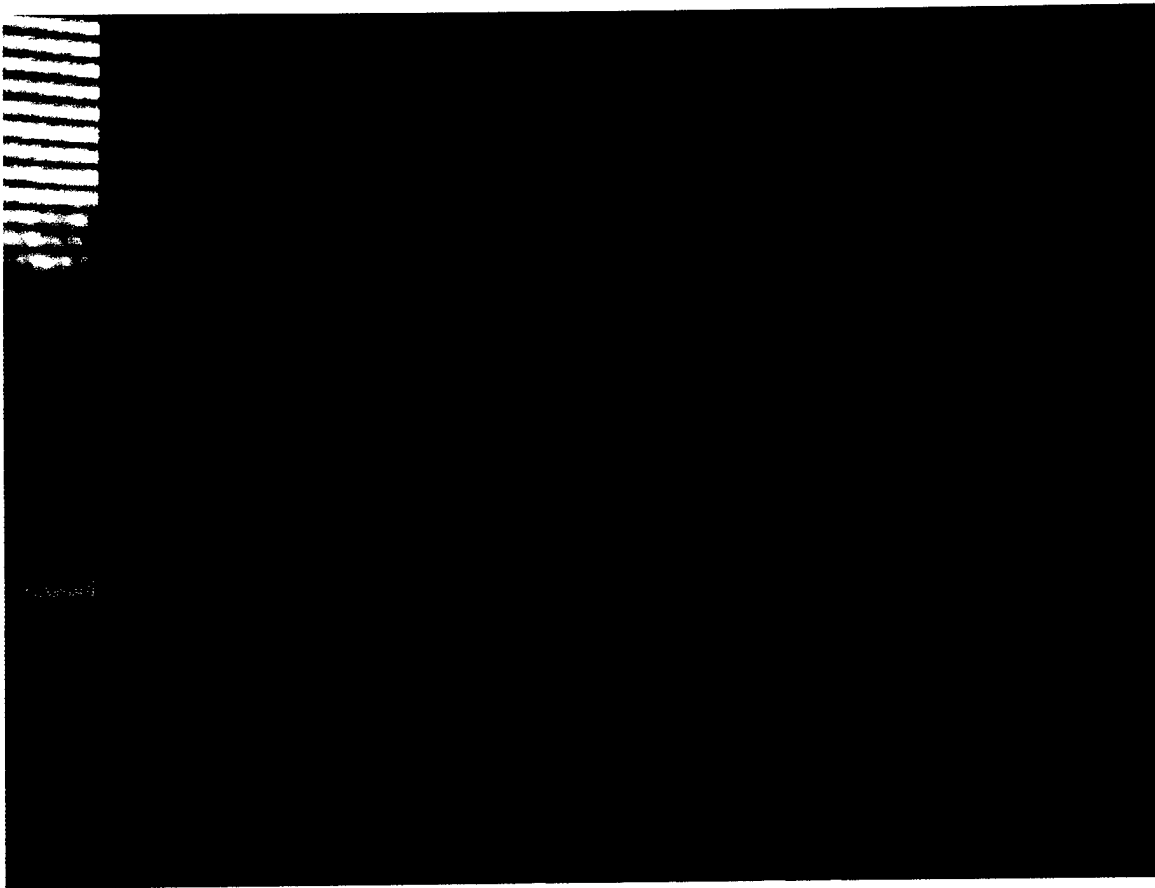


FIGURE 2-2. ASDE-3 DISPLAY OF ATLANTA AIRPORT DEPARTURE QUEUE

3. MULTILATERATION THEORY.

Beacon multilateration offers an alternative to conventional Beacon systems. In multilateration, a signal from the target vehicle is received at several locations. For a geometry with three receivers, a transmitter placed at each unique location within the triangle of receivers, will create a unique set of Time Difference of Arrival (TDOA) values. Conversely, for each set of TDOA values, the unique point from which the signal was emitted can be determined.

3.1 MULTILATERATION CONCEPTS.

Three receivers in an equilateral triangle with a transmitter located at the center would receive a signal transmitted signal at the same time, creating zero time difference between all receivers, as shown in figure 3.1-1.

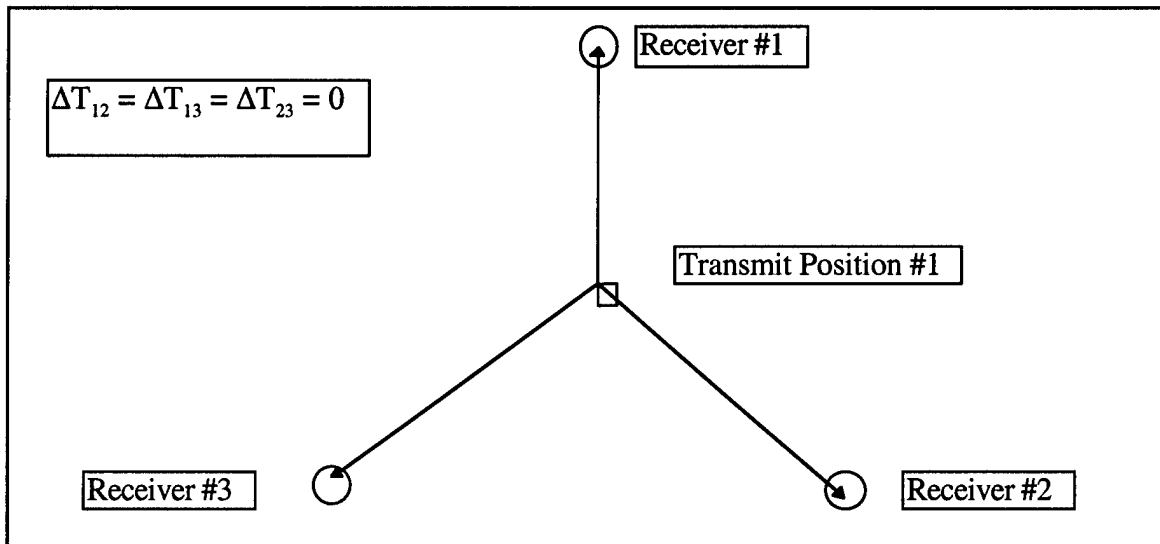


FIGURE 3.1-1. EQUILATERAL RECEIVER TRIAD - CENTRAL TRANSMITTER

Any movement from this point would shorten transmit path to one receiver and lengthen transmit path to the other two receivers. If the movement were along a line from the center toward Receiver #1, the signal would be received at Receiver #1 first. At a later time, signals would be received at Receivers #2 and #3 simultaneously, as shown in figure 3.1-2.

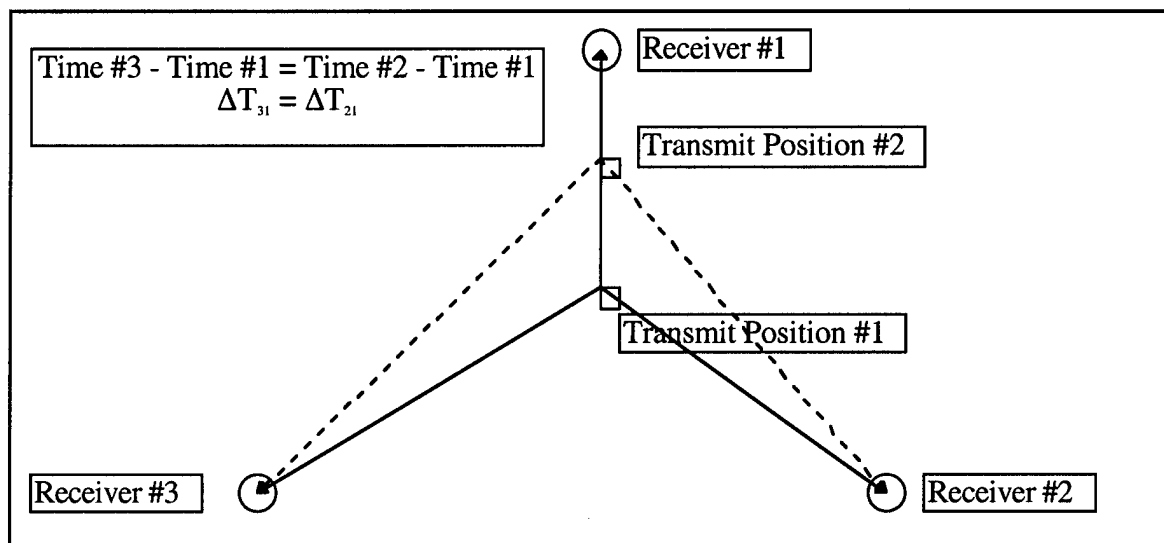


FIGURE 3.1-2. EQUILATERAL RECEIVER TRIAD - TRANSMITTER
BALANCED BETWEEN TWO RECEIVERS

Any additional movement from the line connecting the center to Receiver #1 will cause differences between ΔT_{31} and ΔT_{21} , as shown in figure 3.1-3.

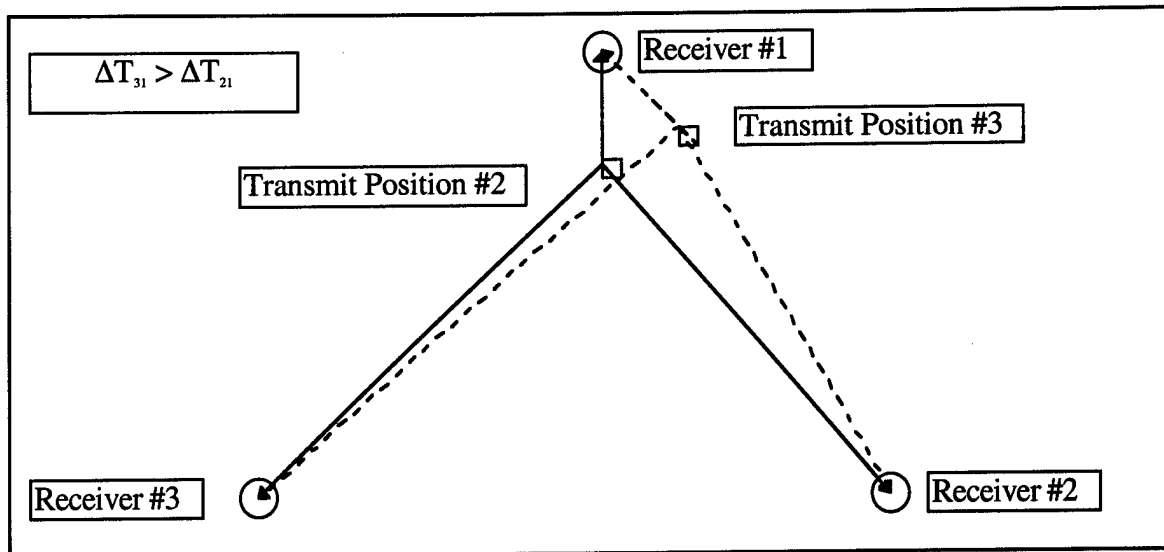


FIGURE 3.1-3. EQUILATERAL RECEIVER TRIAD - TRANSMITTER WITHIN RECEIVERS

It is difficult in a practical application for a group of diverse receivers to keep their clocks aligned to some absolute time reference such as local time or Zulu time. This has been a major problem in other attempts to develop TDOA systems. If absolute time references could be disregarded and the difference in reception times could be accurately measured, then mathematically the only concern is the possible locations the transmitter could occupy for a set time difference between two receivers. For two receivers, the set of possible locations that has the same ΔT is represented by a line or hyperbola, as shown in figure 3.1-4.

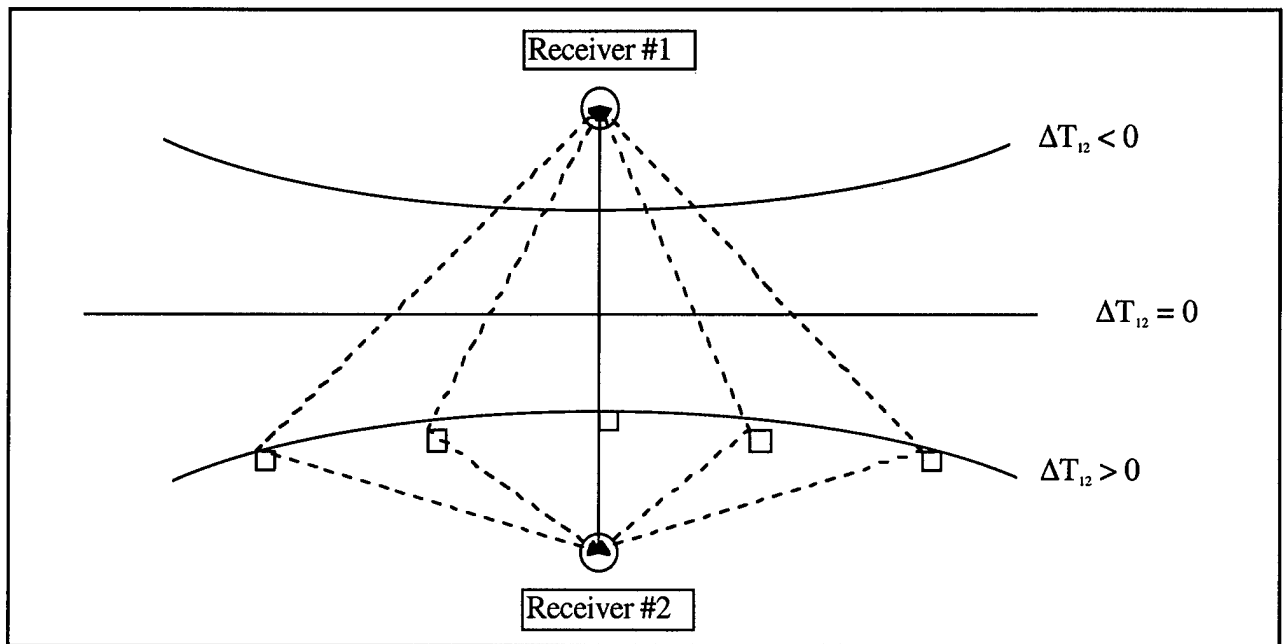


FIGURE 3.1-4. HYPERBOLIC MULTILATERATION WITH TWO RECEIVERS

If a third receiver was used and a line for ΔT_{13} was plotted, then the two-dimensional position of the transmitter could be found by calculating the point of intersection of the two hyperbolas as shown in figure 3.1-5.

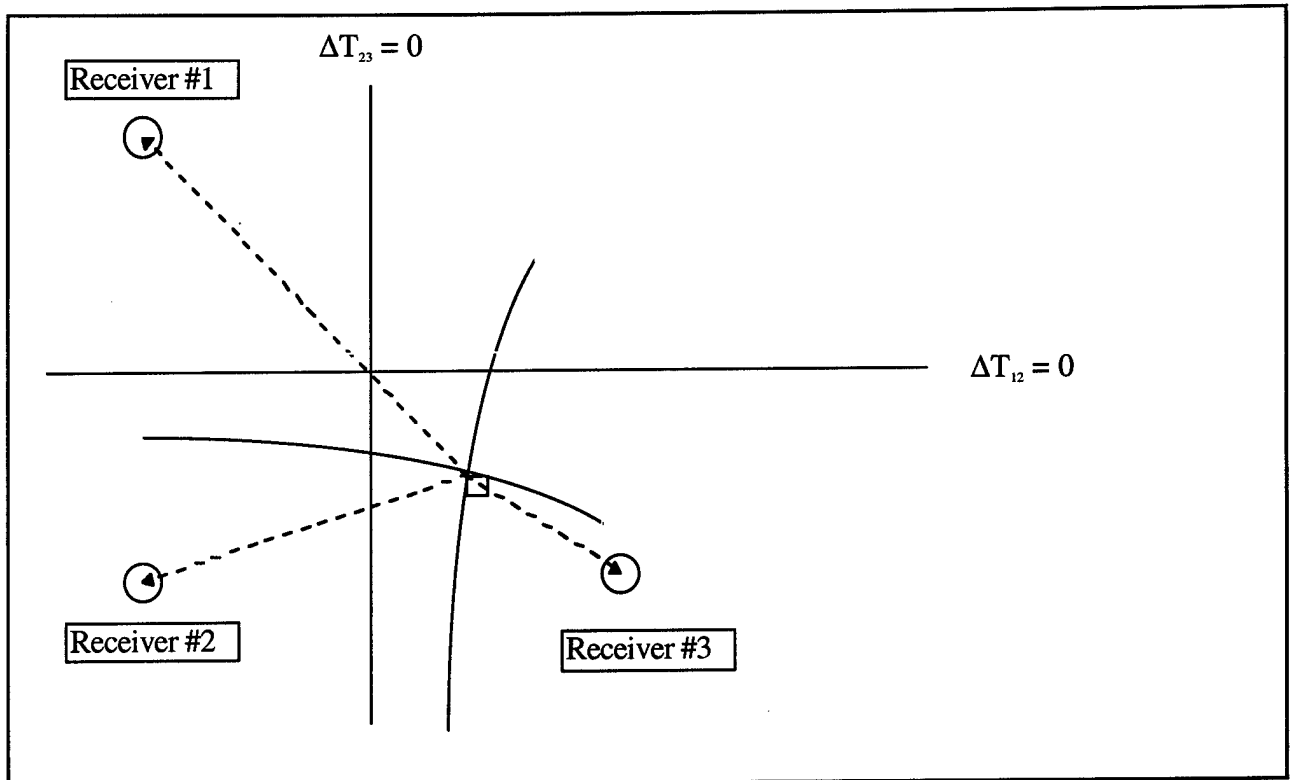


FIGURE 3.1-5. HYPERBOLIC MULTILATERATION WITH THREE RECEIVERS

This concept can be extended into three dimensions with a fourth receiver, but that is beyond the scope of the application.

3.2 MULTILATERATION ERROR SOURCES.

The accuracy of the position calculation is bounded by the ability to measure the exact time differences between receivers which define the hyperbolas, and maximum accuracy that can be obtained is ultimately a function of the clock speed used for time stamping. Other error sources further reduce the accuracy either for a single position calculation or for all position calculations. These error sources fall into two categories; system error and environmental error.

System error components are predictable errors which are introduced because the system hardware and software has a finite ability to receive, time stamp, and calculate position based on legitimate Beacon squitter receptions. One source of error is Dilution of Precision (DOP), which is a magnification of the position calculation error due to the relative position of the receiver and the target. In general, DOP is higher and accuracy is lower as the target gets close to a single receiver. DOP is explained in more detail in section 3-3.

Another system error source is caused by differences in receive amplitude at the different receivers. As the target moves closer to one receiver, the squitter amplitude at that

receiver will be higher relative to the other receivers. The rising edge of a lower amplitude squitter will take longer to cross the receiver's sensitivity threshold than a stronger squitter. Therefore, if the squitter source is close to one receiver, but distant from the other two, the time stamp of the higher amplitude will be biased forward in time. This will cause a position solution that is closer to the higher amplitude R/T reception than the actual position of the squitter source.

The receiver amplitude error is a smaller source of error than DOP, but the two sources will combine near the receivers to create regions of much lower accuracy. Good receiver siting can overcome both of these error sources by ensuring that triad combinations are available that do not include the RT being approached or overflowed.

Environmental error components are nonpredictable errors principally caused by distortion of Beacon squitters prior to reception. These distortions can be the result of blockages, reflections, garbling, multipath, and differences in amplitude at the different receivers. These error sources can occur anywhere in the coverage area, and while it is largely impractical to correct these distortions, methods are available to ensure that corrupt data is detected and eliminated from position calculations.

3.3 DILUTION OF PRECISION (DOP).

The accuracy of a position derived with multilateration is dependent on the receiver geometry and the relative position of the target. The effects of geometry on accuracy are expressed in terms of DOP. A smaller DOP indicates a better geometry, which yields a more accurate position solution. The expected accuracy at a given location can be determined by multiplying the system error (described in section 3.2) times the DOP value. For example, if the system error is found to be 100 meters and receiver to target geometry gives a DOP of 2, the anticipated position error will be 200 meters.

It was shown in figure 3.1-4, that a target exactly between a pair of receivers ($\Delta T=0$) is located along a straight line between the receivers, and for a target with a non-zero ΔT is located on a hyperbola between the receivers. As shown in figure 3.3-1, the closer the target is to a receiver, the higher the curvature of the hyperbola.

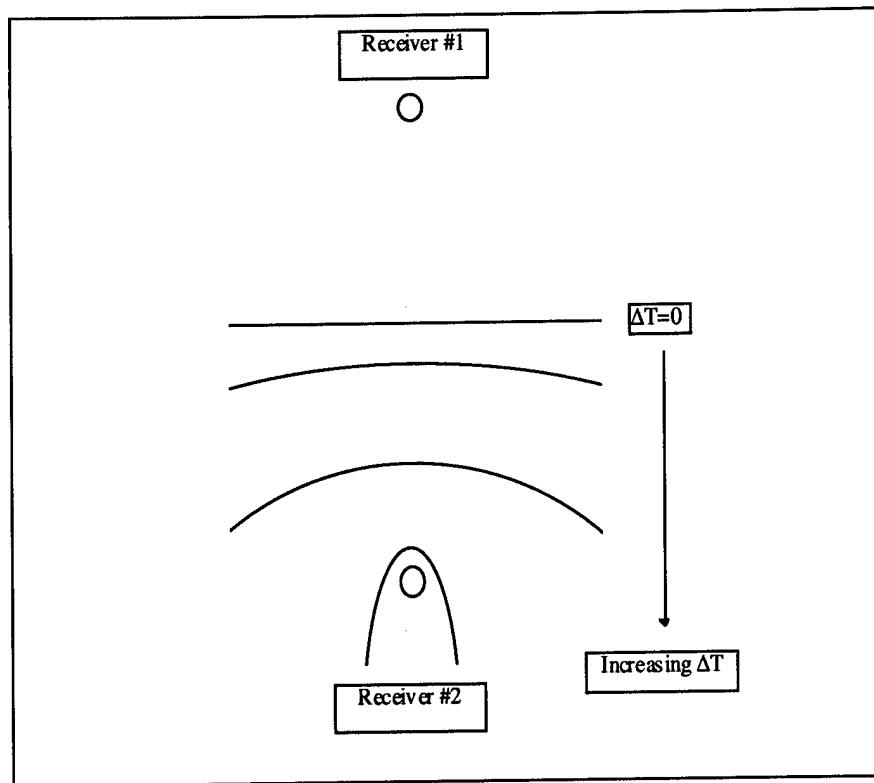


FIGURE 3.3-1. SERIES OF HYPERBOLIC POSITION CURVES

In figure 3.1-5, it was shown that a target can be located by using three receivers to plot a pair of hyperbolic curves and finding the intersection. For any pair of hyperbola created in this manner, there will be two intersection points, as can be seen in figure 3.1-5 by extending the lower and right-hand arc segments. They would eventually intersect again in the lower right-hand quadrant.

This is generally not a problem, as only one solution is normally in or even near the coverage area of the system. When this second solution becomes a problem is when the target moves very close to one of the receivers. As shown in figure 3.3-2, for a target close to a receiver, the hyperbola becomes critically curved, and the two hyperbola intersections occur in close proximity. In this case, choosing the correct solution is not trivial, and the system's ability to determine target position is degraded.

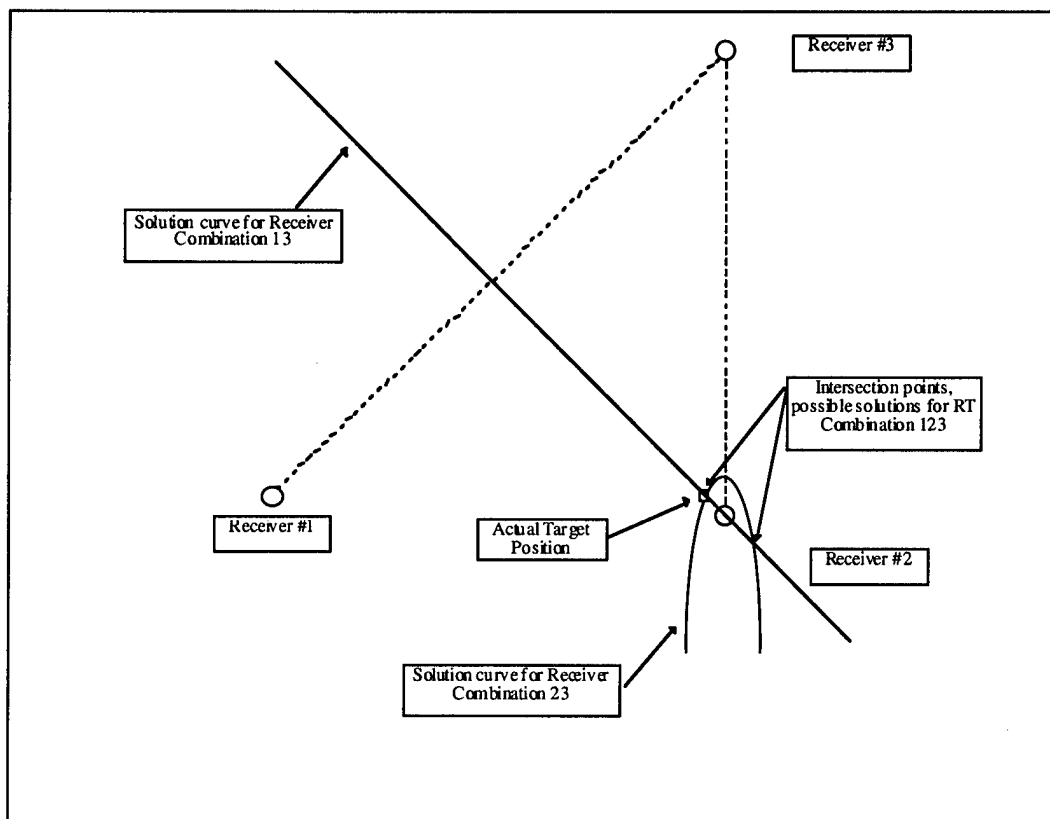


FIGURE 3.3-2. CLOSELY SPACED SOLUTIONS NEAR RECEIVER

Figure 3.3-3 shows the DOP values for locations with the coverage area of a simple three-receiver system arranged in a right triangle.

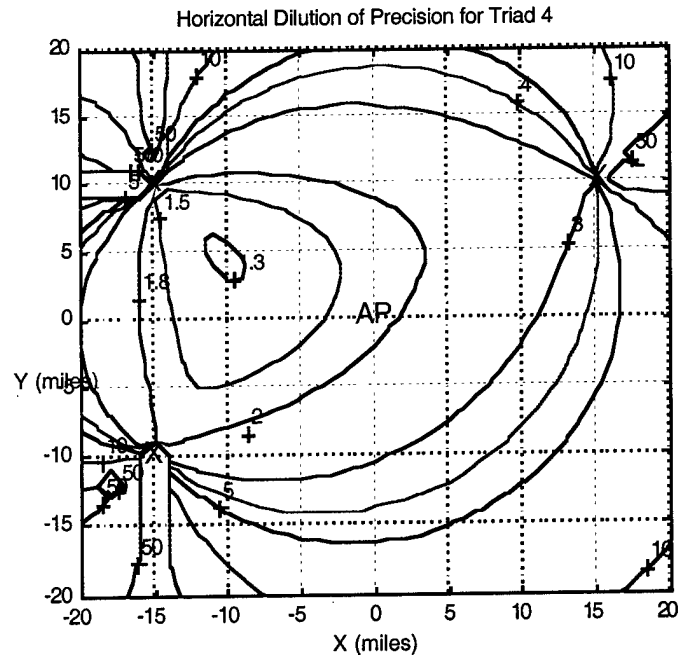


FIGURE 3.3-3. DILUTION OF PRECISION CHART FOR A THREE-R/T MULTILATERATION SYSTEM

In the surface application for CAPTS, the areas of high DOP are easily avoided through good siting and receiver selection. Since the aircraft are constrained to runway and taxiways, the receivers must be sighted outside of the airport movement areas. For systems with more than three receivers, receiver selection logic should be applied to ensure that the position solution is calculated with the best available geometry.

For the airborne applications, it is difficult to ensure that the high DOP can be completely avoided. With complete overlapping sets of receivers, it is theoretically possible to always encircle a target, but it would not be very cost effective. Siting must be selected which provides the greatest accuracy in regions where traffic density is greatest, or where accuracy is most critical.

4. CARDION CAPTS SYSTEM.

The CAPTS system is composed of three types of units:

- a. The Receiver/Transmitter (R/T), three or more.
- b. The Reference Transponder, one or more depending on airport configuration.
- c. The Master Work Station (MWS), only one.

4.1 THE RECEIVER/TRANSMITTER (R/T).

There are at least three R/Ts, and the number varies with airport configuration. Each R/T, shown in figure 4.1-1, consists of a Rockwell Collins Traffic Collision Avoidance System (TCAS) unit, an interface/clock board, a microprocessor board, a power supply, and a modem for transmitting data to the MWS. The equipment is housed in a weatherproof enclosure, and each R/T site has a beacon frequency antenna, which may be directional or omnidirectional. The modem may be wired, if a dedicated phone line is available between the R/T and the MWS, or may be an RF modem which requires an additional antenna.

The TCAS unit receives Beacon frequency replies and decodes Mode S messages. The interface/clock card also monitors Beacon frequencies and contains a high stability 10 nanosecond (ns) clock. Its output is latched each time the rising edge of the first pulse of a Beacon message is received. The microprocessor board stores the clock output until the TCAS unit can decode the message to obtain the ID contained in the message. The ID and time stamp are output to the modem and transmitted to the MWS.

The R/T also has the ability to transmit and receive long format Mode S messages and to transmit Air Traffic Control Radar Beacon System (ATCRBS) interrogations. The Mode S messages permit the R/T to perform Mode S Automatic Dependent Surveillance (ADS) functions such as Global Positioning System (GPS) correction uplinks and position and message downlinks. The ATCRBS interrogations allow the system to track ATCRBS-equipped aircraft. Aircraft equipped with these older style transponders do not emit the once-per-second squitter found in Mode S-equipped aircraft, so it is necessary to interrogate to create a reply to perform a multilateration calculation on.



FIGURE 4.1-1. CAPTS SYSTEM R/T UNIT

4.2 THE REFERENCE TRANSPONDER

There is one reference transponder, although the system could easily be modified to use more than one for complex airport configurations. The reference transponder is a standard

Mode S transponder in ground mode. It is sited at a known location within the coverage of all R/Ts and is housed in a weatherproof enclosure with an omnidirectional Beacon frequency antenna.

The transponder is set to operate in Ground Mode. In Mode S Ground Mode, the unit emits standard ground squitters once-per-second and does not reply to interrogators such as those on FAA ASRs. These ground squitters allow the MWS to dynamically offset the error in each R/T's 10 ns clock. This can be done because the location of the reference transponder and each R/T are known, so the same set of ΔT values should always be received.

4.3 THE MASTER WORK STATION (MWS).

There is only one MWS. It consists of two personal computers (PC), two displays, and a modem for each R/T. One PC contains all of the interfaces to other parts of the system and performs the position calculations. The second PC is for display processing. One display shows a map of the airport with target symbols and information, and the second display is for control and maintenance functions.

The MWS receives the ID and time stamp information from all R/Ts. Within these messages are the reference transponder squitters, which the MWS uses to calculate differences in the R/T clocks. The R/T clocks are stable over short periods of time, but drift relative to each other. The reference transponder squits permit updating of the relative offsets once per second. The MWS first corrects the time stamps of all received ID reports. Before calculating the position, the MWS selects an R/T triad using the following methodology:

- a. If less than three R/Ts have reported, no position calculation is performed.
- b. If only three R/Ts have reported the squat, the position is calculated using those R/Ts.
- c. If more than three R/Ts have reported the squitter and the ID is currently under track, a table of preferred triads for the last known position is used to select the highest ranking triad of available R/Ts, and the position is calculated.
- d. If more than three R/Ts have reported the squat and the ID is a new track, the first three R/Ts to report are used to calculate a first position.

For existing tracks, the MWS sanity checks the new position and updates the track. A track is started for new reports, and tracks are updated on the MWS display. The MWS

also acts as the control and configuration interface for the system. The MWS also has the ability to display Mode S ADS GPS positions if they are received.

5. ATLANTIC CITY SYSTEM.

The Cardion CAPTS system was installed in a four-R/T configuration beginning in November of 1993. The system underwent cycles of development and testing throughout late 1993 and early 1994. Typically, a cycle would consist of Cardion deploying their system at Atlantic City for a 1-week period to collect data and make software changes, and then returning the equipment to Cardion's Long Island Facility for hardware and software modifications. The testing was kept informal with a focus on measuring the results of improvements and directing further development.

Concurrent with the multilateration surveillance work, Cardion was also permitted to explore the Mode S data link applications of the CAPTS system. In early 1994, Cardion signed a joint agreement with Unisys and Rockwell Collins to participate in a joint demonstration of Mode S data link technologies. Rockwell Collins had been supporting Cardion in the Multilateration CRDA and Unisys secured a separate CRDA with the FAA Technical Center. Together, the three companies demonstrated an aircraft equipped with GPS receivers could receive GPS corrections uplinked by the CAPTS system and then downlink its corrected GPS position via the CAPTS system or the rotating Mode S sensor. The demonstration also demonstrated that other messages, such as taxi clearances, could also be uplinked and downlinked via the CAPTS system.

5.1 ATLANTIC CITY INSTALLATION.

The first task in the installation was the selection of four sites for the R/Ts and one site for the reference transponder. Several parameters were established to guide R/T site selection, and those requirements for the sites were:

- a. A location was required near the end of each runway (total of four).
- b. Each location must have access to 115 volts alternating current (VAC) power.
- c. Each location must have access to dial telephone lines.
- d. Each location must have an unobstructed view of all or most of the airport surface.
- e. The optimum antenna height was 35 feet above the runway surface.

The antenna height figure was based on an earlier study of multilateration conducted by Cardion at Atlantic City, which had shown the potential for vertical multipath garbling of replies. This is a condition where the transmission from an aircraft or from the reference transponder is reflected from the runway surface and causes interference with the direct transmission, as shown in figure 5.1-1. A return of this type will not be decoded by the TCAS unit, or it will be decoded incorrectly.

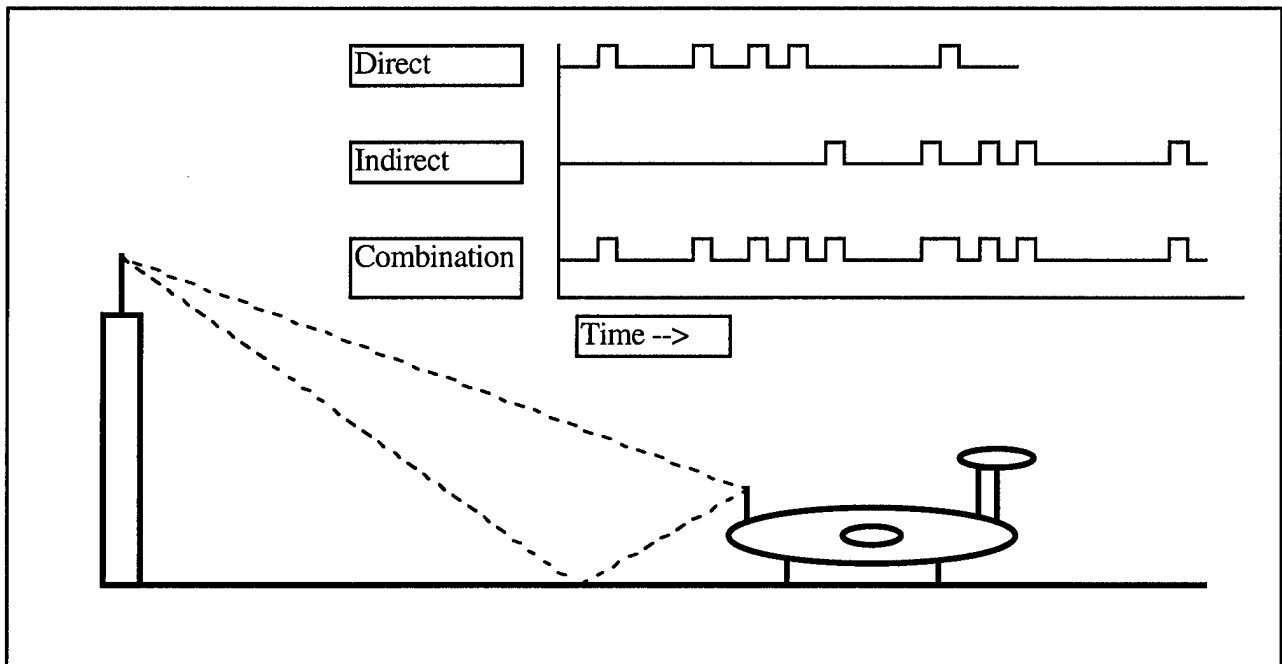
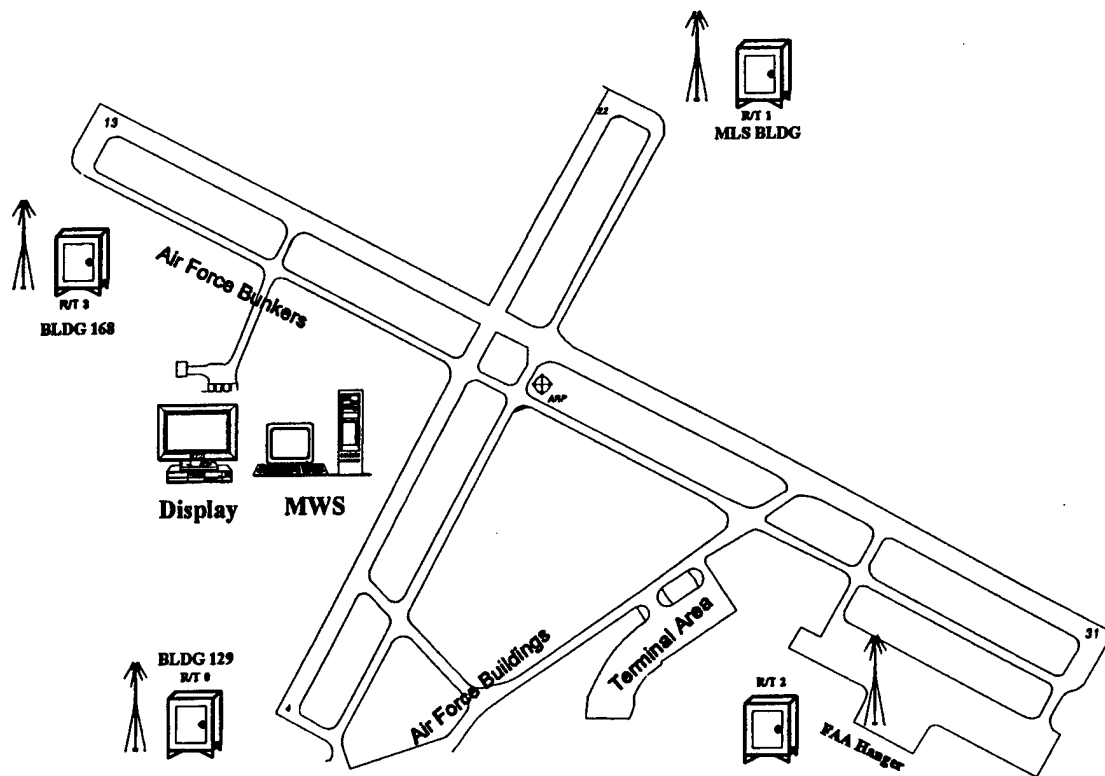


FIGURE 5.1-1. VERTICAL MULTIPATH INTERFERENCE

Based on these parameters, the locations shown in figure 5.1-2 were selected.

Initially, the system was planned with only wired modems, so an initial requirement for siting was access to existing dial telephone lines. During the installation, it was discovered that existing lines on the airport were in poor condition and could not be used. To allow the start of testing, Cardion provided several sets of 9600 baud (Bd) spread-spectrum modem which are commercially available and operate at a public band of approximately 900 megahertz (MHz). The modems proved very effective and added a great deal of flexibility. Modems at three of the sites were upgraded to a 56-kilobaud (Kb) model of spread-spectrum modem in the same band, and one site remained hard wired and was also run at 56 Kb to demonstrate that the system could be run on either wired or wireless modems.



CAPTS DEPLOYMENT AT ATLANTIC CITY INTERNATIONAL AIRPORT

FIGURE 5.1-2. ATLANTIC CITY R/T LOCATIONS

It was quickly discovered that the 35-foot antenna height was problematic. Terrain blockages were causing very limited coverage area for R/T's 0 and 2. Multilateration requires that the target be visible from a minimum three out of the four available R/Ts, so solutions were only being calculated on a very limited area of the airport. To resolve this problem, R/T 2 was moved from the Radio Communications Link (RCL) tower location to the roof of the FAA Technical Center Hanger and the antennas for R/Ts 1 and 3 were raised to 50 feet. The antenna for R/T 1 could not be raised as it was close to the approach of a runway.

As a result of the move, coverage improved and the vertical multipath that had been anticipated was not seen. Coverage of the airport was not complete because of the low height of R/T 1, but the full length of the 10,000-foot runway at Atlantic City was visible to the remaining three R/Ts. The only area not covered was the end of runway 4-22 furthest from R/T 1.

During this same time period, the Cardion engineers had a major breakthrough in improving their system accuracy. A series of instructions had been left in the microcode for the Collins TCAS unit which were executing periodically. When these instructions would execute, they would delay the output of the decode by several milliseconds (ms).

For a TCAS unit operating in an aircraft, this delay has no effect because of other delays related to the airborne display. In this multilateration application, this delay would cause one of the time stamps to be incorrect resulting in a position error of 200 feet. Testing at the Collins plant by a team of Cardion and Collins engineers discovered and resolved this undocumented code fragment.

At this point, events led to the system being moved to Atlanta before final testing could be conducted at Atlantic City. There were still two outstanding problems which were preventing final testing. The first was the siting of R/T 1 which was preventing full coverage of the airport. The second was a method for aligning the clocks of the CAPTS system and the FAA Technical Center's Laser Tracker. The differences in the clock were causing a bias in the position reports when the target was in motion. The systems were located at two remote locations on the FAA Technical Center grounds. It was decided that GPS time could be used to provide a common reference.

Static testing with aircraft and vehicles was performed on November 30 and December 1, 1994. During this testing the system was also demonstrated to representatives of the Surface Program Office in FAA Headquarters. As a result of the demonstration, it was decided that the system had sufficient merit to be moved to the Atlanta Hartsfield International Airport in Atlanta, GA, to provide a denser traffic environment.

5.2 ATLANTIC CITY DATA COLLECTION.

The data collected on November 30 and December 1, 1994, demonstrates multilateration accuracy consistent with the system which was later installed in Atlanta. No improvements were made to the CAPTS system between Atlantic City and Atlanta which would make the system more accurate. The principal difference between the Atlantic City and Atlanta data is that the Atlantic City data were collected on stationary targets and that a more accurate ground truth reference source was used. The laser tracker that was used was a GTE Precision Automated Tracking System (PATs) Laser Tracker. Its azimuth and elevation accuracy are +/- 20 ArcSeconds @ all ranges. Its range accuracy is:

+/- 1 foot for ranges < 5 nautical miles (nmi).

+/- 2 feet for 5 to 10 nmi.

+/- 5 feet for ranges at 25 nmi.

The PATs laser tracker is a monopulse-type tracking system. It uses quadrant detection from a (near) infrared (1.06 micrometer (μm)) frequency laser as a source. The azimuth and elevation encoders are 18 bits (just under 5 arcseconds/bit). The range resolution is 1 foot.

Two test vehicles were used during the testing, a large panel van (see figure 5.2-1) and a Beechcraft 200 Aircraft (see figure 5.2-2). Both were outfitted with a standard Mode S transponder and an optical reflector for the Laser Tracker. In the case of the vehicles, the Mode S antenna and reflector were placed 1 foot apart on a metal plate atop the vehicle. In the case of the aircraft, the Mode S antenna and reflector were 5 feet apart on the aircraft fuselage. Since this testing was scheduled as intermediate evaluation and not final testing, no method was used to compensate for the error caused by the spacing of the antenna and reflector. If the heading of the aircraft and vehicle could have been logged, this error could have been removed.

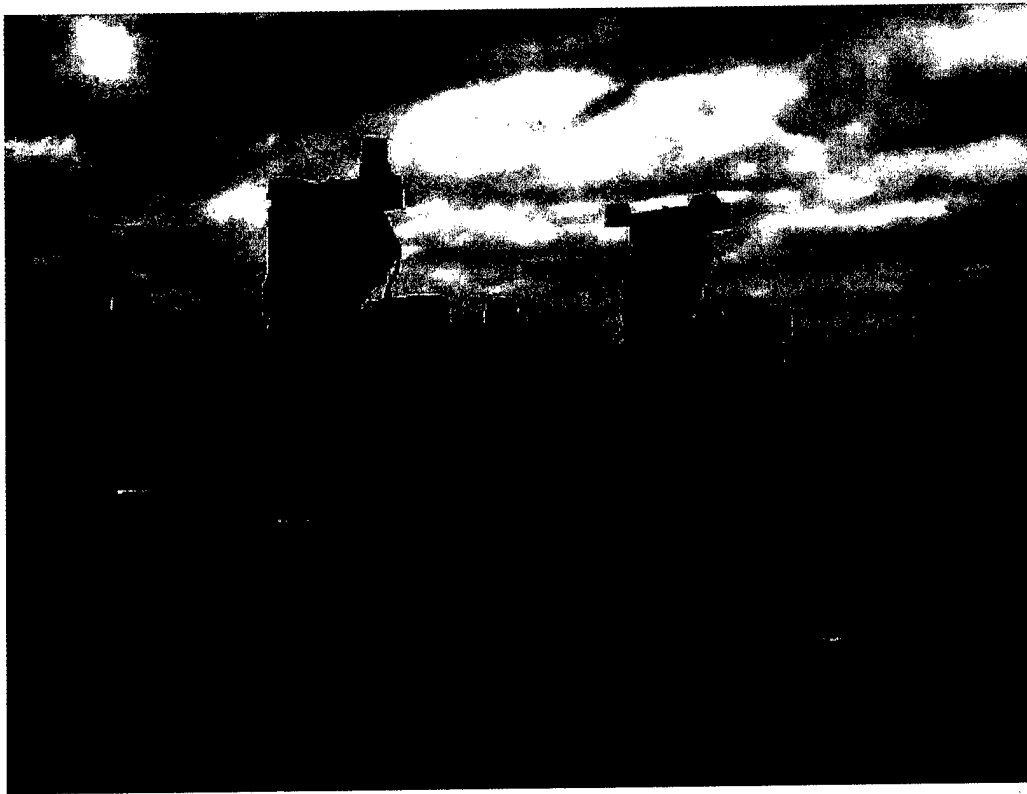


FIGURE 5.2-1. GROUND TEST VEHICLES

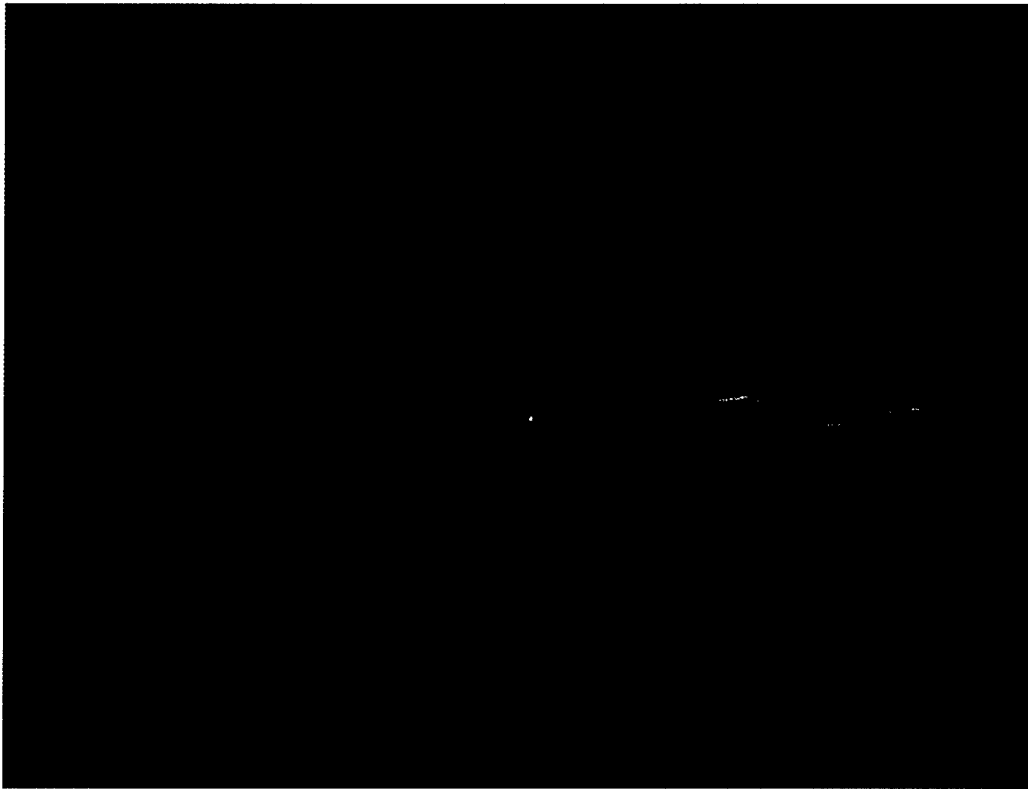


FIGURE 5.2-2. TEST AIRCRAFT, CONVAIR 580 (L) AND BEECHCRAFT 200 (R)

Data was collected for a total of 14 locations on the airport, as shown in figure 5.2-3. The vehicle was used for nine locations and the aircraft was used for the other five. At each location, the vehicle was stopped and kept stationary for a period of approximately 5 minutes. In some cases there is less data because the target vehicle was required to yield to other surface traffic on the runways and taxiways. Position data was collected by both the CAPTS system and the Laser Tracker.

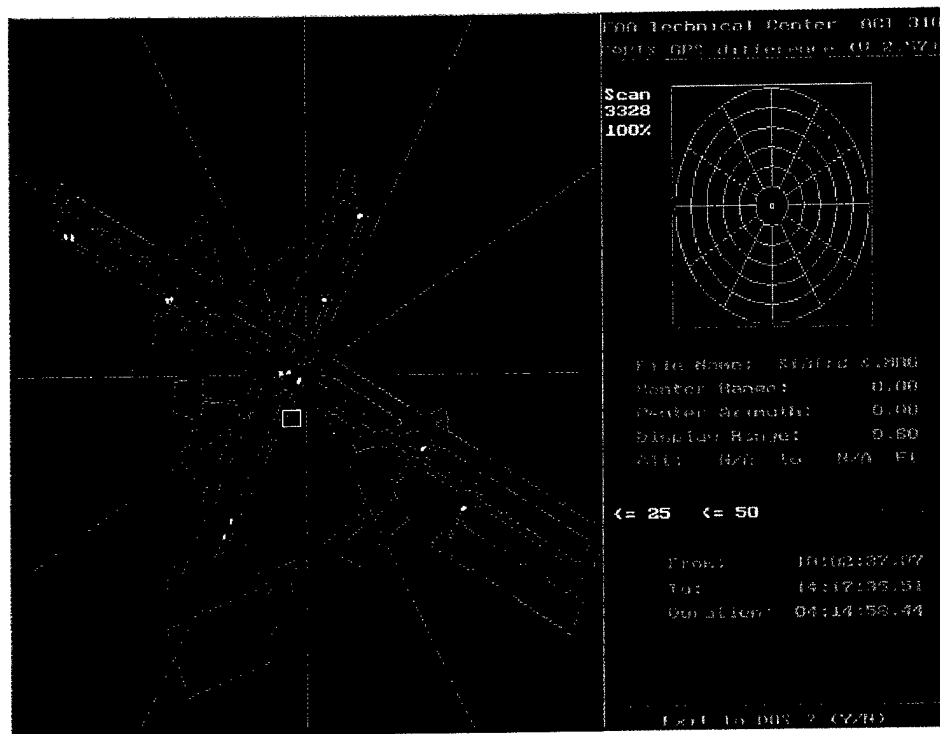


FIGURE 5.2-3. ATLANTIC CITY AIRPORT TEST DATA COLLECTION LOCATIONS

5.3 ATLANTIC CITY MULTILATERATION ACCURACY RESULTS.

The system demonstrated performance in line with theoretical expectations for this simplified static data test case. The Atlantic City tests do not provide results on the performance of the tracking algorithms used in the system and do not represent any error which would be added by those algorithms. Because of the small baseline between the R/Ts and the lack of target motion, this presents a good example of "best case" data (see figures 5.3-1 through 5.3-3). The average distance error between the CAPTS system and the Laser Tracker was 23.41 feet. The sample size was 2469 points, with a standard deviation of 13.478 feet. This yields an RMS distance error of 27.013 feet. The worst case distance error was 98 feet. The colored dots in this and subsequent charts indicate the CAPTS position, and the color indicates the difference in position from the truth system. This is an example of CAPTS versus Laser Tracker and in later charts, examples of CAPTS versus Carrier Phase Tracked Differentially Corrected GPS will be shown.

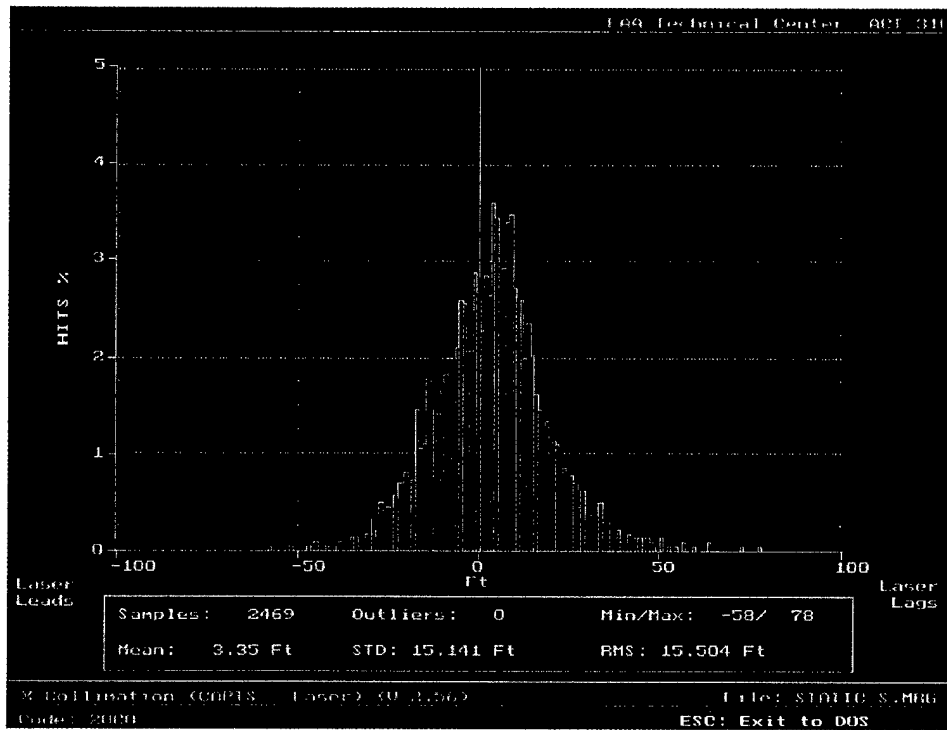


FIGURE 5.3-1. ATLANTIC CITY AIRPORT TEST DATA, EAST-WEST ACCURACY

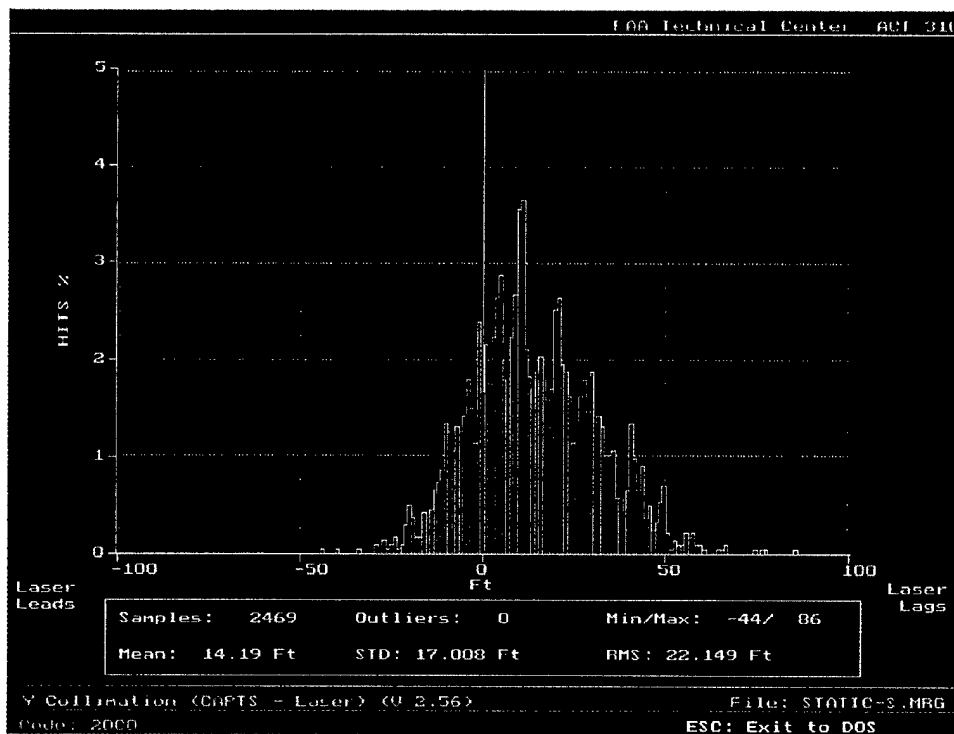


FIGURE 5.3-2. ATLANTIC CITY AIRPORT TEST DATA, NORTH-SOUTH ACCURACY

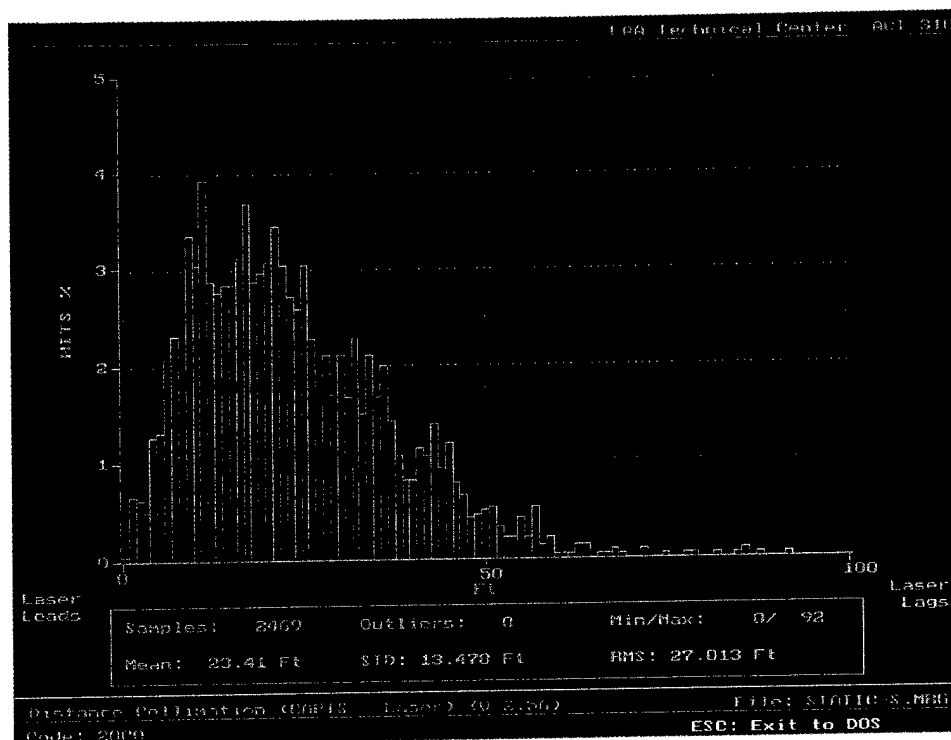


FIGURE 5.3-3 ATLANTIC CITY AIRPORT TEST DATA DISTANCE ACCURACY

6. ATLANTA SURFACE SYSTEM.

Cardion received a contract to install their system at Atlanta's Hartsfield International Airport. The contract was funded by the FAA Surface Program Office and was managed by Massachusetts Institute of Technology Lincoln Laboratories (MITLL). This contract included the leasing of a five-R/T system which was installed to provide coverage of the north side of the airport, which consists of two parallel runways, interconnecting taxiways and part of a ramp area. The four R/Ts from Atlantic City were moved to Atlanta, and Cardion constructed a fifth R/T.

The Cooperative Research and Development Agreement (CRDA) was extended to provide the opportunity for additional evaluation of the system. Data was collected to provide additional multilateration accuracy measurements on Mode S-equipped aircraft and vehicles. MITLL's evaluation of the system was concentrated in two areas. The first was to explore methods for choosing optimum R/T locations to maximize coverage and minimize multipath effects. The second was to explore methods for tracking aircraft equipped with older ATCRBS transponders. Since these transponders do not emit squitters, a scheme had to be employed to create a unique reply which could be multilaterated. MITLL and Cardion attempted a Whisper Shout interrogation scheme similar to that used in TCAS.

This technology remains under development, and currently provides the most promising means for tracking ATCRBS transponders. It does this at the expense of system capacity, due to the large number of interrogations required to perform the Whisper Shout. The exact nature of the performance tradeoff cannot be determined until work on this technology is completed.

6.1 ATLANTA SURFACE INSTALLATION.

Due to the availability of tall buildings at the Atlanta Airport, installation of towers was not necessary. R/Ts and antennas were installed on five buildings as shown in figure 6.1-1. Instead of placing the R/Ts near the ends of the runway, as in the Atlantic City installation, two R/Ts were placed to the north of the runways and three R/Ts were placed to the south, in lines parallel with the runways. This R/T configuration created a series of triangular areas spanning the runways. R/Ts were placed (clockwise from the upper left) on the FAA Regional Headquarters, the Stouffer's Concourse Hotel, the Ford Automobile Assembly Plant, the Delta Aircraft Maintenance Hanger, and the roof of Hartsfield Concourse C.

The reference transponder was also sited on the Stouffer's Concourse Hotel. It was placed as far from the R/T as possible to prevent saturation of the R/T by the reference transponder squitters. The MWS was placed in Atlanta Tower, and R/Ts communication between the R/Ts and the MWS was accomplished with the RF Spread-Spectrum modems used in Atlantic City.

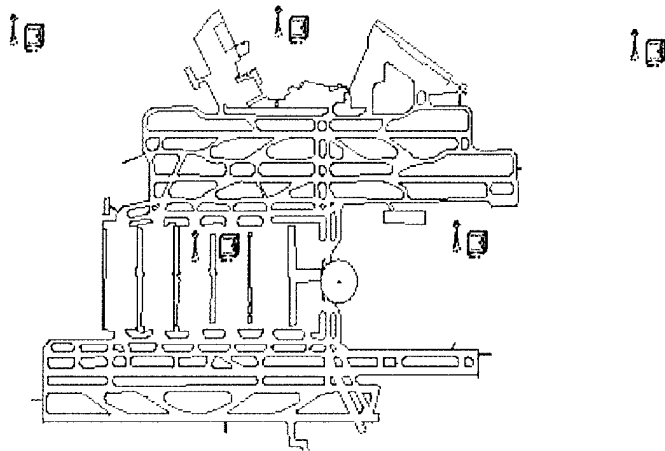


FIGURE 6.1-1. ATLANTA HARTSFIELD AIRPORT (ATL) SITING FOR SURFACE SURVEILLANCE

6.2 ATLANTA SURFACE DATA COLLECTION

Data was collected from January 16 through 18, 1996, using a Convair 580 aircraft (see figure 5.2-2). Differential GPS was used to establish ground truth on the aircraft, because there were no tracking radar assets available at the Atlanta Airport. The aircraft was equipped with a Rockwell Collins Pallet identical to a unit used during the Mode S data link demonstrations in Atlantic City. The pallet contained a GPS receiver, an Airborne Data Link Processor (ADLP), and a Mode S transponder with firmware to support long squitter data link formats. The CAPTS system was connected to a GPS Ground Station which had been used during previous data link demonstrations, and this unit supplied the CAPTS system with dynamic GPS corrections.

The GPS corrections were uplinked to the aircraft using a Mode S broadcast format (UF-20). The aircraft would then downlink its corrected position twice per second in a long format airborne squitter. The CAPTS system would multilaterate on the message, provided it was received at a minimum three R/Ts and would also strip the corrected GPS position from the long format message and store both positions. The GPS position would serve as the reference system, with the multilateration position being the system under test.

It was initially thought that this would solve the time alignment problem which prevented the collection of dynamic data in Atlantic City, inasmuch as both measurement methods were derived using the same incoming squitters. Unfortunately, there was additional collection error created by this method. The GPS positions were buffered in the ADLP prior to downlink, awaiting the next twice per second squitter cycle. This introduced a time difference between the multilateration position and the GPS position. The multilateration position is time tagged immediately upon being received, but the GPS data in the message could be up to one-half second old. This introduces a position bias in the data that is proportional to the velocity of the aircraft.

This error was immediately evident in the collected data, and was manifest as a bias where x-axis GPS position lagged x-axis multilaterated position. The error in the Atlantic City data was evenly distributed, as the multilateration method does not favor any particular orientation or origin. A conventional radar has less error at close ranges from the antenna, and the error increases with distance. Additionally, characteristics which control azimuth accuracy are different from those which control range accuracy. Multilateration error is essentially uniform within the triangle of receivers, and increases rapidly over the R/Ts outside the triangle. Since we intentionally site the R/Ts to surround the airport surface, we get more uniform accuracy.

The error that was found due to the time difference was situated along the x-axis because of the orientation of the runways. Atlanta's runways are situated almost directly east to

west, and the flight profiles had the aircraft both arriving from the west and departing to the east. Since the aircraft is moving substantially faster during takeoff and landing, this created a time delayed GPS position to indicated positions to the west of the multilateration positions.

Even if very accurate position and velocity data was collected, the error could not be removed because the squitter delay varied randomly from near 0 ms to 500 ms. Instead of attempting to remove the error, the effect of the error could be minimized by eliminating the high speed portions of the data. During takeoff and landing, velocities can exceed 200 mile/hour, but during taxiing, the aircraft velocity typically does not exceed 20 miles/hour. With an average of 250 ms delay time and a worst case velocity of 20 knots, the average worst case error we would expect would be:

$$\frac{20 \text{ Mile}}{\text{Hour}} = \frac{29.33 \text{ Feet}}{\text{Second}} \times 0.25 \text{ Seconds} = 7.33 \text{ feet}$$

The data collection was accomplished using a Convair 580 aircraft equipped with the GPS-ADLP-transponder pallet described above. Three approaches were flown to Runway 8L on 2 consecutive days. The aircraft was taxied to an unoccupied area of taxiway and collected 5 minutes of stationary data. The aircraft was then taxied to Runway 8R and departed. The data has been truncated as described above to remove the high speed portions of the arrival and departure.

6.3 ATLANTA SURFACE MULTILATERATION ACCURACY RESULTS.

The system demonstrated performance in line with expectations for this simplified dynamic data test case, and the results are shown in figures 6.3-1 through 6.3-4. The average distance error between the CAPTS system and the Differential GPS system was 29.48 feet. The sample size was 1623 points, with a standard deviation of 20.846 feet. This yielded an RMS error of 36.099 feet. The worst case distance error was 184 feet. There is a slight increase in error over the Atlantic City data, which is normal and caused by the longer baseline between the R/Ts, as described in section 3.2.

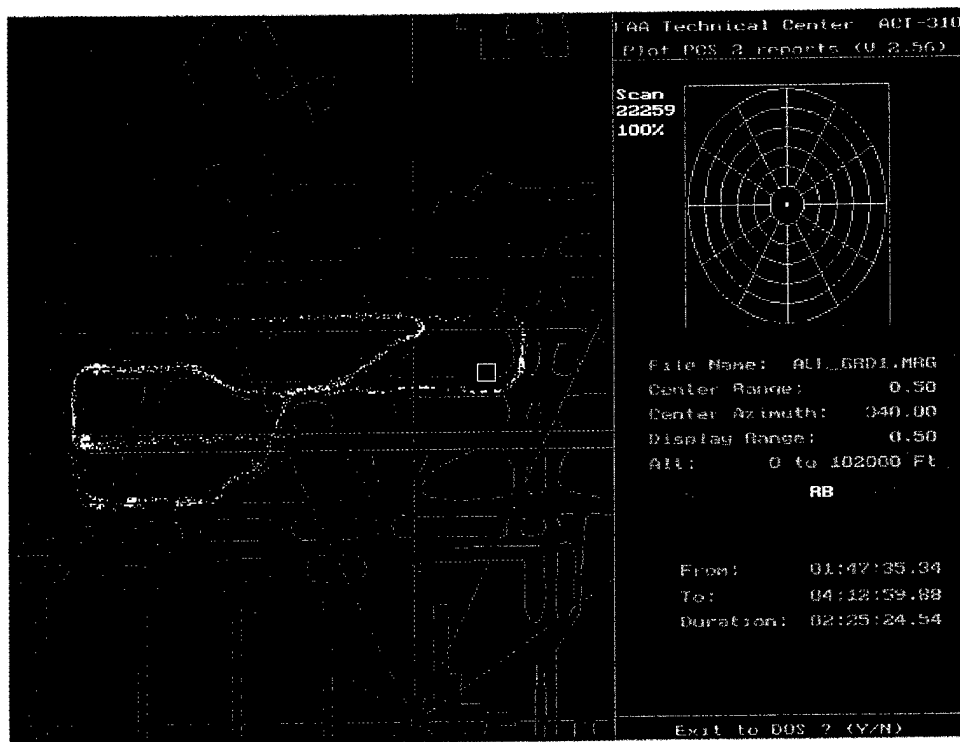


FIGURE 6.3-1. ATLANTA HARTSFIELD AIRPORT SURFACE TEST DATA

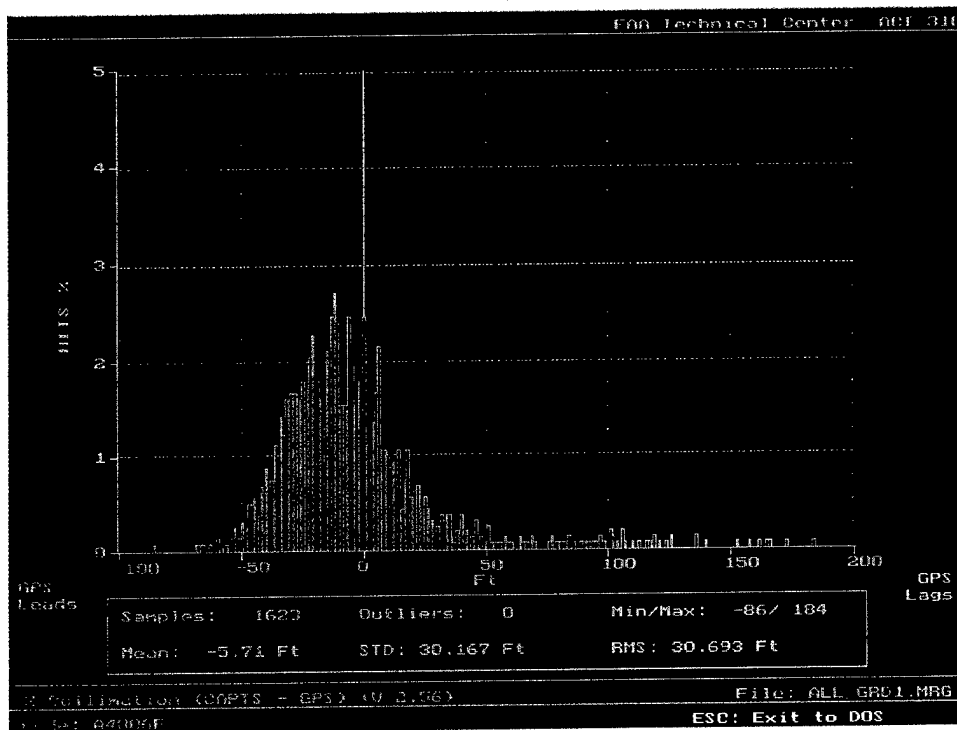


FIGURE 6.3-2. ATLANTA HARTSFIELD AIRPORT TEST DATA, EAST-WEST ACCURACY

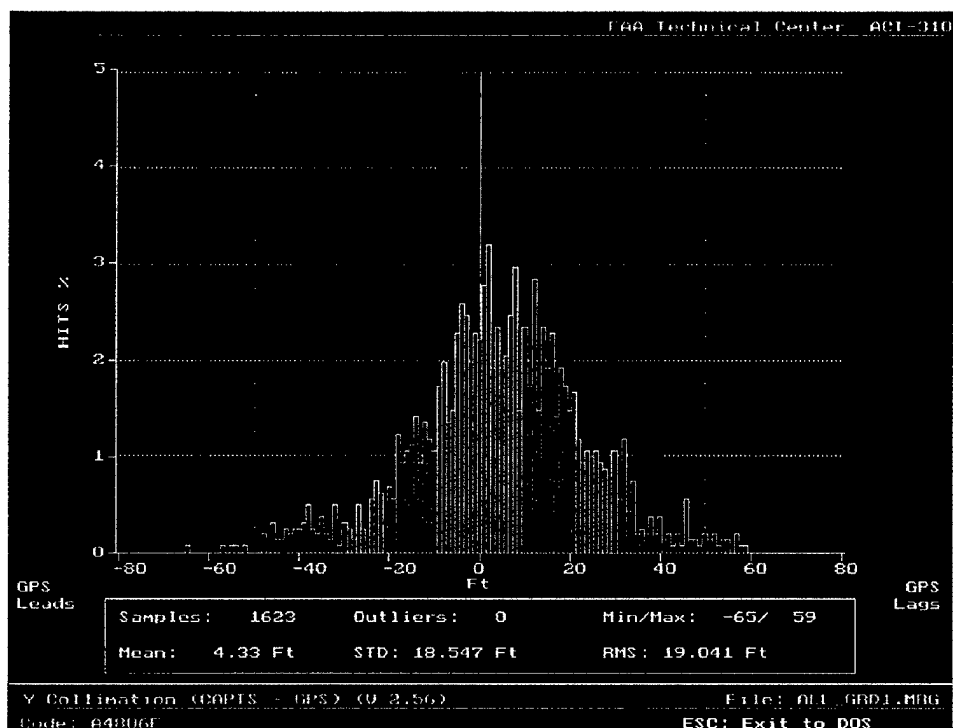


FIGURE 6.3-3. ATLANTA HARTSFIELD AIRPORT TEST DATA, NORTH-SOUTH ACCURACY

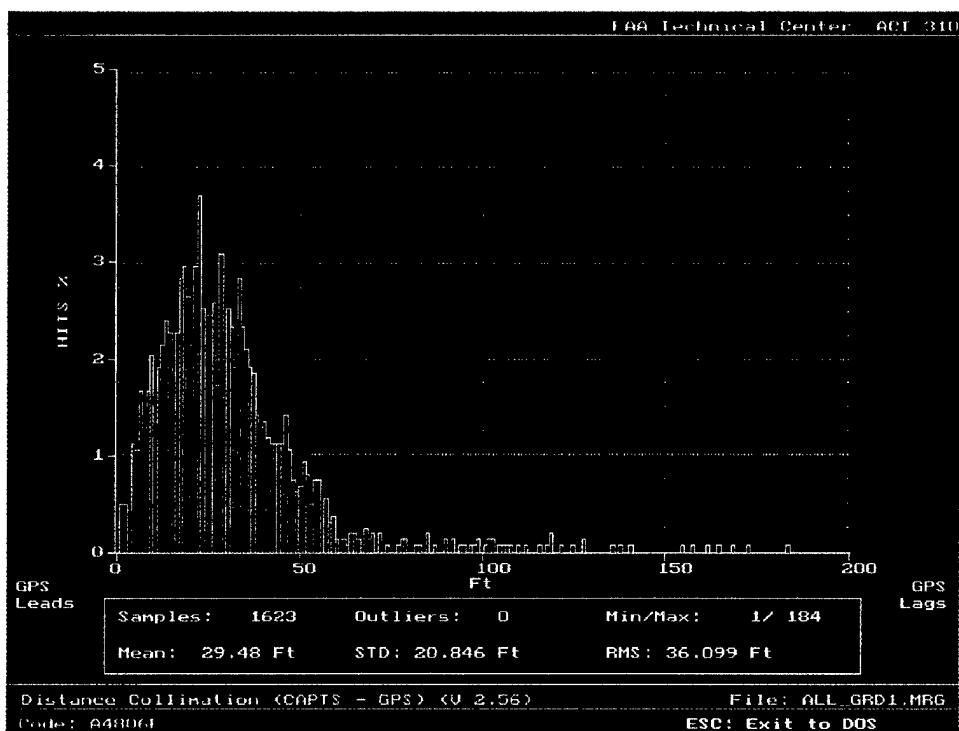


FIGURE 6.3-4. ATLANTA HARTSFIELD AIRPORT TEST DATA DISTANCE ACCURACY

7. ATLANTA PARALLEL RUNWAY MONITOR (PRM) SYSTEM.

In September 1996, the R/Ts were reconfigured to demonstrate that the multilateration concept could be applied to airborne aircraft. The FAA's PRM program will install systems at five airports which provide better monitoring and control of aircraft on final approach to closely spaced runways. Cardion set out to demonstrate that a multilateration sensor could provide sufficient coverage, accuracy, and update rate for use in the PRM application. The FAA's PRM Program Office performed a cost estimate and determined that a four-R/T system would cost between \$700K and \$950K which would be less than the electronically scanned system currently being installed.

In the Atlantic City and Atlanta installations, the system was sited for surface targets. Multilateration is effective in tracking both surface and airborne targets, and many of the multipath and blockage problems that are encountered on the surface are greatly reduced or eliminated for airborne targets. It would be necessary to move the R/Ts much further apart than in either of the surface applications. In Atlantic City, the greatest distance between R/Ts was approximately 9000 feet (1.5 miles), while in Atlanta this distance was approximately 15,000 feet (2.5 miles). In order to place R/Ts around the approach it would be necessary to place them up to 10 miles from the MWS and up to 15 miles apart. This provided an opportunity to examine the effect of this on system performance, as well as explore the logistical aspects of communicating the R/T data across these distances.

7.1 PARALLEL RUNWAY MONITOR (PRM) BACKGROUND.

The PRM system is an electronically scanned beacon radar system and specialized displays which provides high update rate coverage of runway approaches. It is installed at airports with closely spaced parallel runways to provide controllers with highly accurate aircraft position data and alerts in the event of potential conflicts.

The radar's antenna does not rotate but instead consists of an array of 128 antennas in a circular configuration. By applying the transmitted pulse to a series of these antennas, a beam is formed which radiates outwardly perpendicular at the center of the antennas used. By adjusting the phase to each antenna, the beam can be steered left or right. In this way, the antenna array can form beams along any radial to a high degree of angular accuracy. The beams do not have to be adjacent as they would with a rotating antenna but can be created in any radial direction beam to beam. The nominal update rate is once per second for all targets but can vary up or down with target load and individual target priorities.

The display for PRM (see figure 7.1-1), also known as the Final Monitor Aid (FMA), provides a controller with a scalable large screen display which presents the runway

approaches separated by a no-transgression zone (NTZ). The display provides alert algorithms with target predictors, a color change alert when a target penetrates or is predicted to penetrate the NTZ, a color change if the aircraft's transponder becomes inoperative, and synthesized voice alerts.

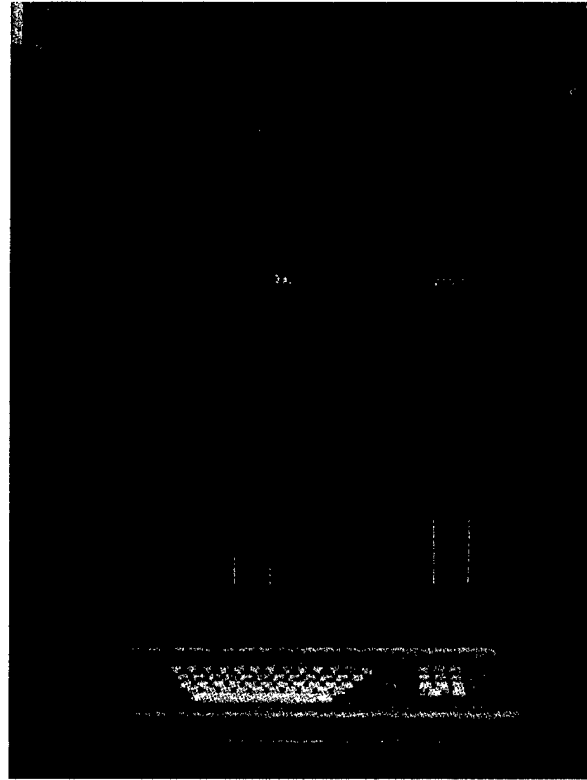


FIGURE 7.1-1. FMA DISPLAY

7.2 ATLANTA PRM SYSTEM INSTALLATION .

After initial site surveys by MITLL, the eastern approaches into Atlanta Hartsfield were selected for the CAPTS/PRM demonstration. This was due to the greater availability of tower sites on that side of the airport. Three R/Ts were repositioned to surround the eastbound approach ends of Atlanta Hartsfield's four runways (see figure 7.2-1). The three remaining R/Ts from the surface installation were kept in their original locations with their beacon antennas turned to optimize coverage of the runway approaches. The MWS and reference transponder were kept in their original locations. The RF spread-spectrum modems were again used to provide communication between the R/Ts and the MWS.

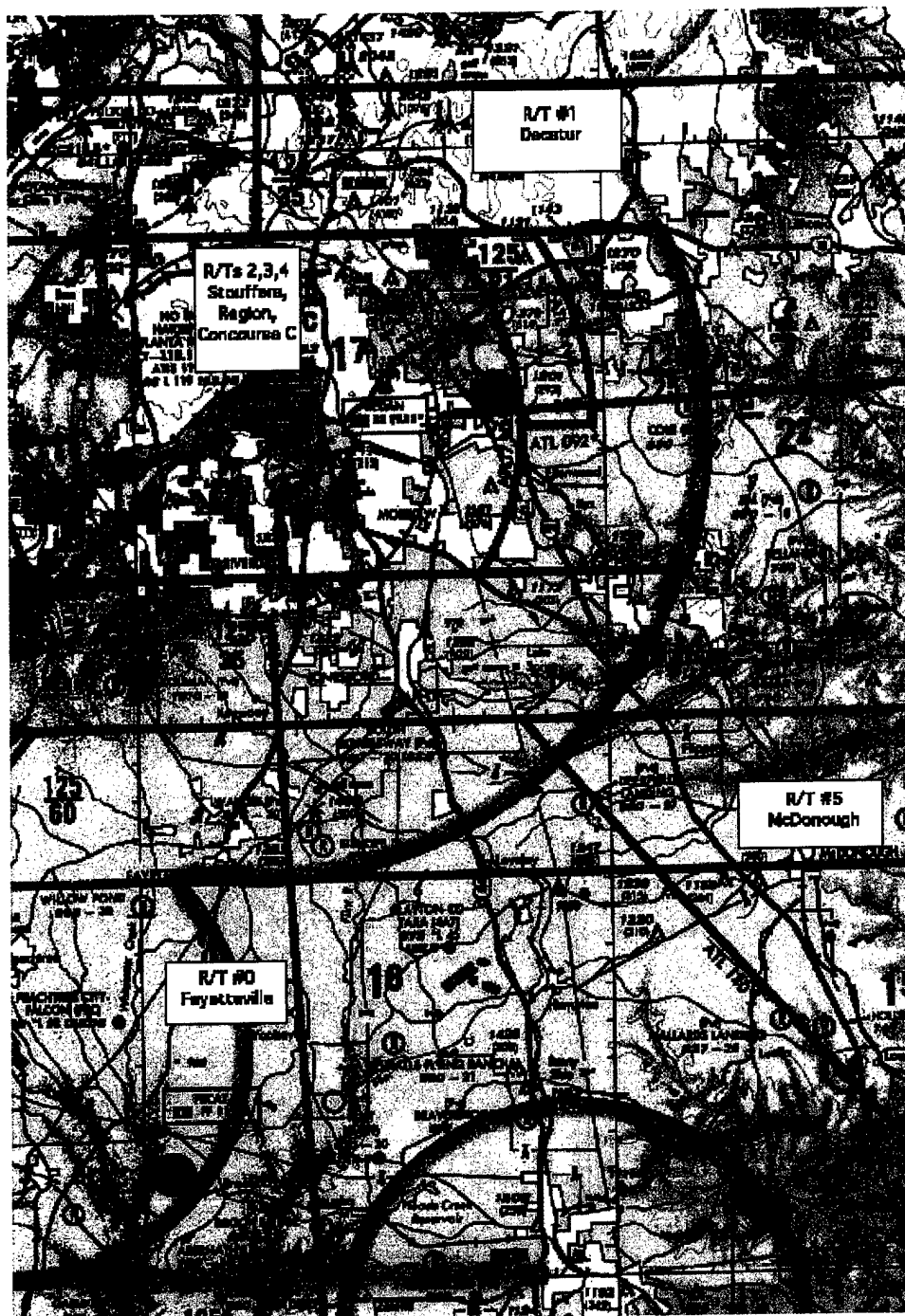


FIGURE 7.2-1. ATLANTA PRM R/T LOCATIONS

7.3 ATLANTA PRM SYSTEM DATA COLLECTION.

Data were collected on January 13 and 14, 1997, and again on February 3 and 4, 1997. The data were collected using two Convair 580 aircraft. Because of the problem with the downlinked GPS positions during the surface testing, each aircraft was equipped with a

GPS receiver connected to a laptop computer. Position information was logged to the computer at a rate of once per second. A GPS base station was installed at a surveyed location on the surface, and data was logged from that system during each flight. Software available from the manufacturer of the GPS base station (MagnaVox) created GPS differential corrections, and post-corrected the aircraft data.

Three types of flight data were collected; approach flights, R/T overflights, and coverage patterns.

7.3.1 Approach Flights.

A set of six approaches was flown to Runway 26L and Runway 27R. Each set consisted of:

- a. One approach on glideslope.
- b. Four approaches slightly off glideslope; one each high, low, left and right of glideslope.
- c. One zigzag approach.

These approaches were chosen because of their ability to stimulate responses from the FMA safety logic.

7.3.2 R/T Overflights.

Multilateration accuracy is highly dependent on the geometry between the squitter source and the R/Ts. To maintain position accuracy, the aircraft position should be derived using R/Ts which surround the aircraft. This is easily accomplished for taxiing aircraft by siting R/Ts off of the airport surface. In tracking airborne aircraft, proper receiver selection is critical to prevent poor accuracy results. Figures 7.3.2-1 through 7.3.2-4 show the DOP multipliers for four of the possible R/T triads in the Atlanta PRM installation which were depicted in figure 7.2-1.

In this test, the aircraft was flown over each R/T so that worst case accuracies can be measured.

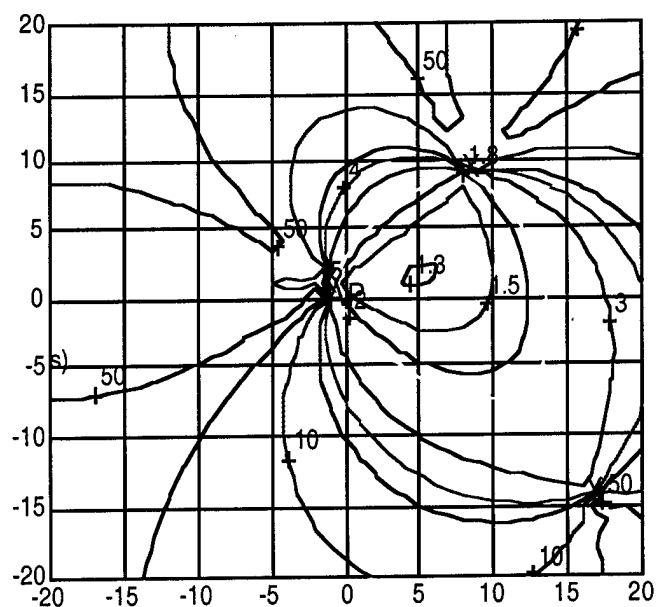


FIGURE 7.3.2-1. HORIZONTAL DILUTION OF PRECISION (HDOP), ATLANTA
PRM RT TRIAD 125 (DECATUR, STOUFFERS, MCDONOUGH)

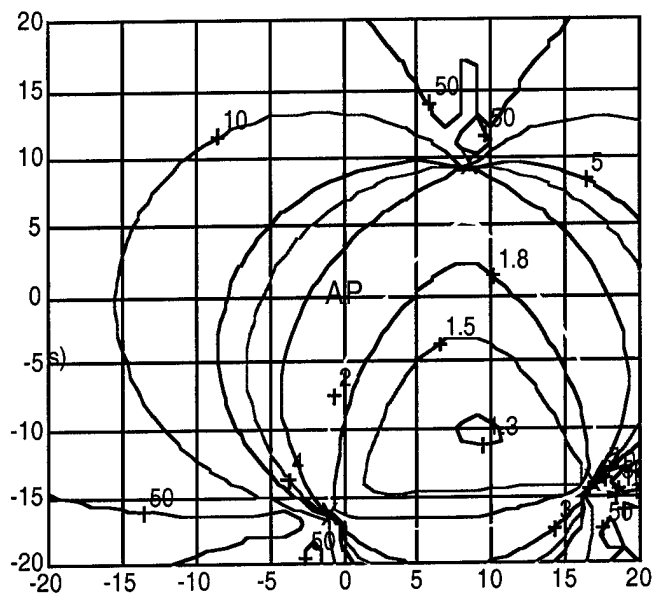


FIGURE 7.3.2-2. HORIZONTAL DILUTION OF PRECISION (HDOP), ATLANTA
PRM RT TRIAD 015 (FAYETTEVILLE, DECATUR, MCDONOUGH)

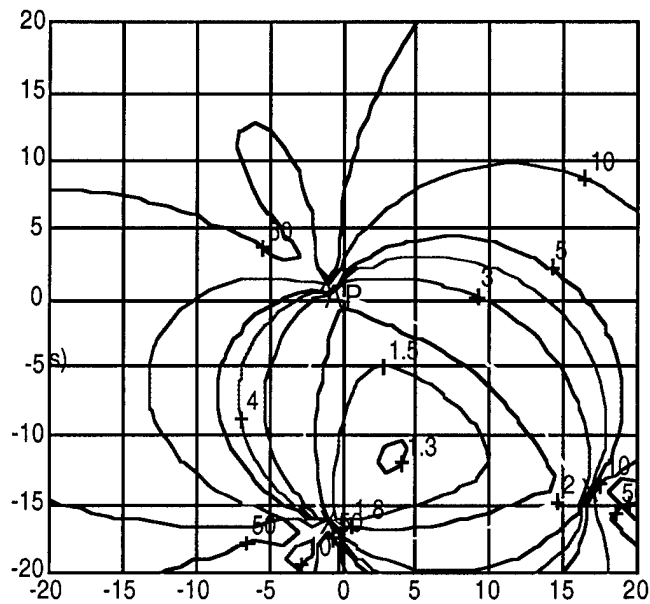


FIGURE 7.3.2-3. HORIZONTAL DILUTION OF PRECISION (HDOP), ATLANTA PRM RT TRIAD 025 (FAYETTEVILLE, STOUFFERS, MCDONOUGH)

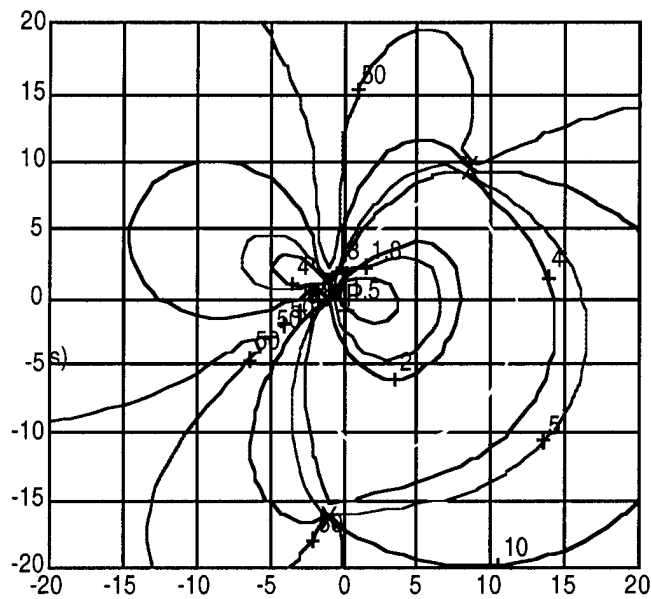


FIGURE 7.3.2-4. HORIZONTAL DILUTION OF PRECISION (HDOP), ATLANTA PRM RT TRIAD 012 (FAYETTEVILLE, STOUFFERS, DECATUR)

7.3.3 Coverage Patterns.

An aircraft was flown in a serpentine pattern (see figure 7.3.3-1) over the coverage area to measure the uniformity of accuracy within the coverage area and to measure the degradation of accuracy as aircraft enter and leave the optimum coverage area.

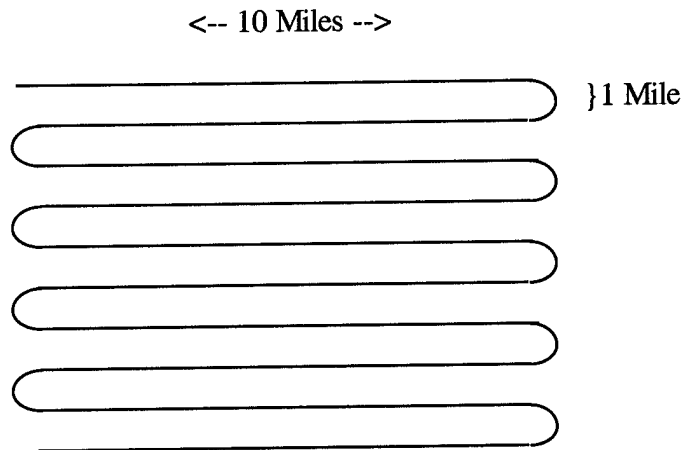


FIGURE 7.3.3-1. COVERAGE FLIGHT PATTERN

7.4 ATLANTA PRM SYSTEM ACCURACY RESULTS.

It should be noted that the data in this section is not the original data output by the system during the flight testing. During those flights two types of data were recorded on the CAPTS system; CAPTS IN files and CAPTS OUT files. CAPTS IN files, which are the raw reports from each R/T, containing only the Mode S ID and the time stamp. This file contains raw reports for any aircraft in the area as well as the reports for the Reference Transponder. CAPTS OUT files contain the calculated x and y position of any target which was received at three or more R/Ts, along with Mode S ID, Mode C altitude, triad used, and other target information.

After analysis, the original CAPTS OUT file was found to have a high percentage of relatively accurate reports, but also a significant percentage of very inaccurate reports. Engineers at Cardion examined the data and discovered a problem in the portion of the software that maintains tracks of active targets to permit the receiver selection algorithm to choose the best triads for a certain geographic area. The tracking parameters had not been changed from the setup used on the surface and were completely ineffective in maintaining tracks. Without this track maintenance, the receiver selection algorithm did not work properly, and the accuracy was effected.

Flights were not repeated at this point due to the reconfiguration of the R/Ts back to the surface surveillance configuration. Instead, an MWS was setup with the tracker

parameters corrected, and the original CAPTS IN files were rerun through the MWS to create new CAPTS OUT files.

Unfortunately, this new data was only a minor improvement over the old data. Once again, the engineers at Cardion examined the bad reports and this time determined that there was a second setup problem. The original surface configuration had consisted of six R/Ts placed around the north side of the airport. The 2D multilateration only requires three R/Ts to calculate a position, but because of blockages from buildings, more R/Ts improve the system coverage on the surface. Fewer R/Ts were required for the PRM demonstration, inasmuch as flying aircraft are not subject to these blockages. It was decided to move only three R/Ts from the surface and leave three behind to support ongoing surface surveillance work.

The bad reports were being caused by triads consisting of two or more surface R/Ts being used to calculate the position of aircraft which were several miles from the airport. Once again the solution was to lock out these triads from the receiver selection table and rerun the CAPTS IN files through the MWS. This data was used to create the charts in this section. The PRM approaches are shown in figures 7.4-1 through 7.4-4. Figures 7.4-5 through 7.4-8 show all of the flight testing, including RT overflights and coverage flights.

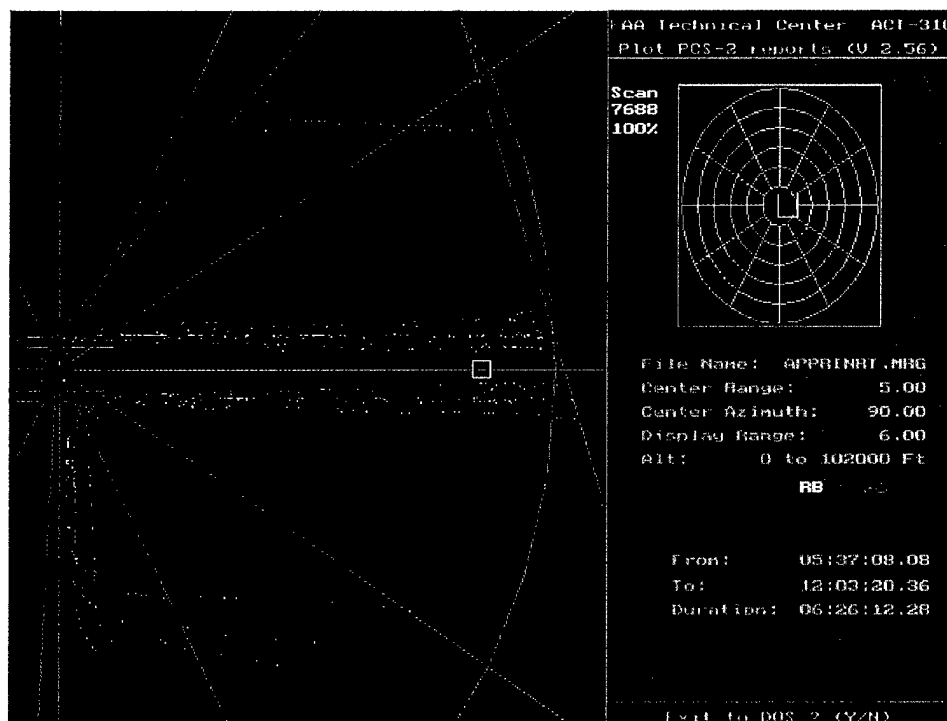


FIGURE 7.4-1. APPROACHES TO ATLANTA, FILTERED FOR R/T AREA AND PRM ALERT WINDOW

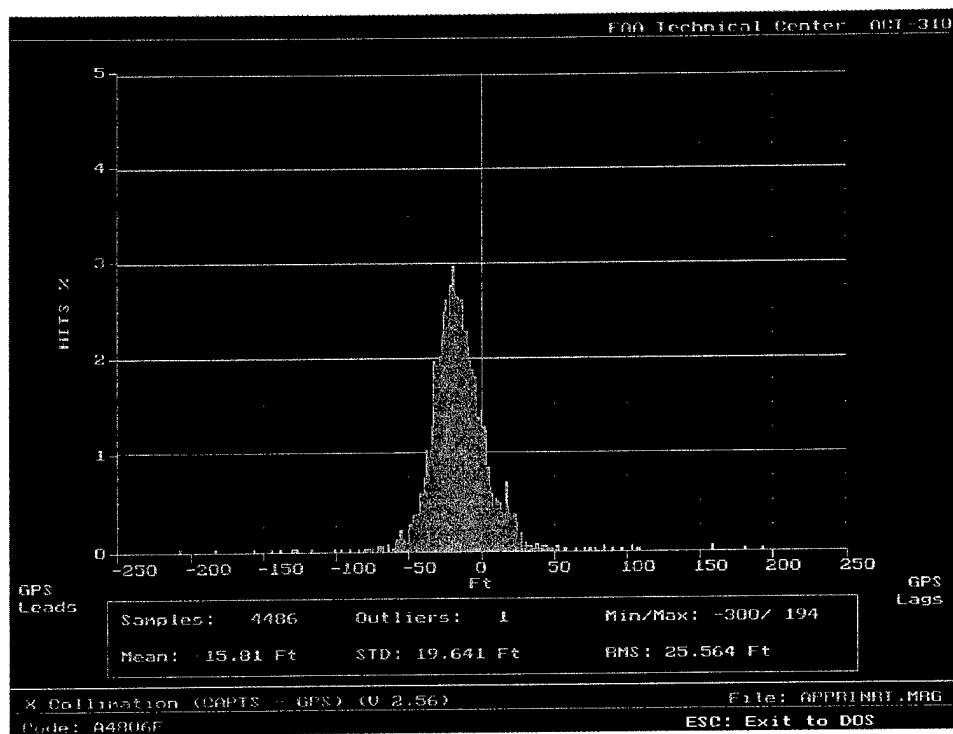


FIGURE 7.4-2. ATLANTA APPROACHES, EAST-WEST ACCURACY

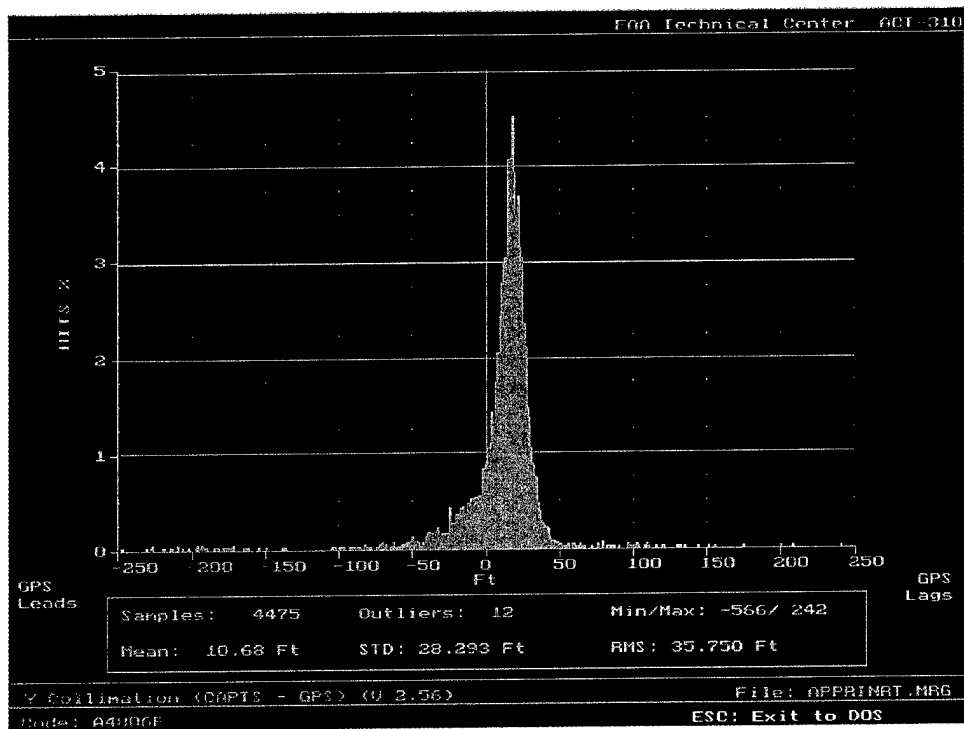


FIGURE 7.4-3. ATLANTA APPROACHES, NORTH-SOUTH ACCURACY

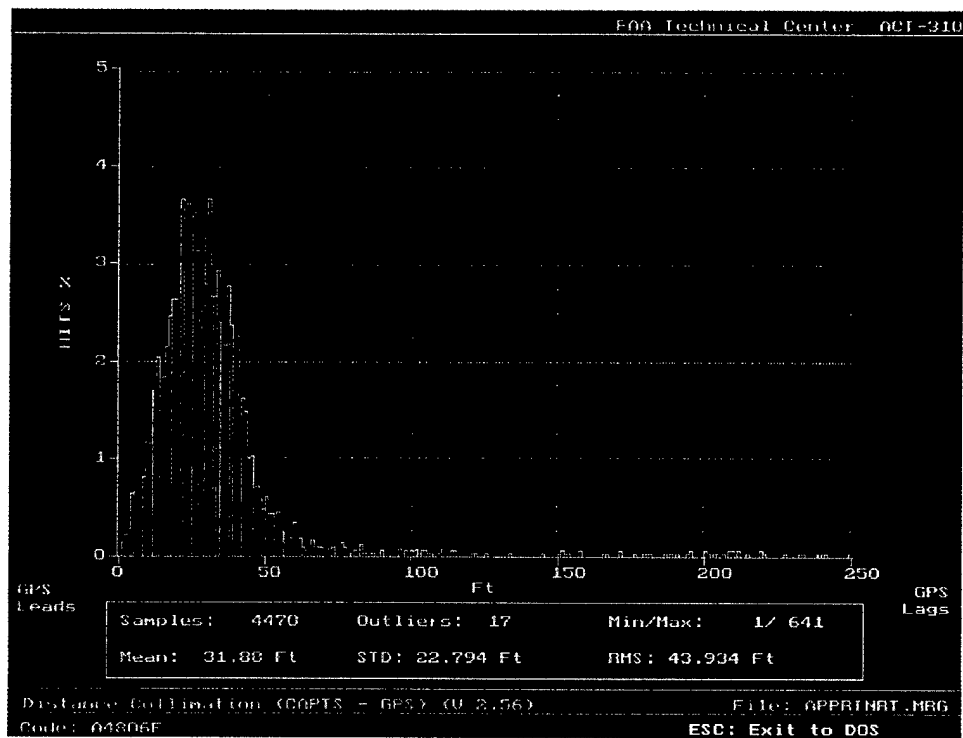


FIGURE 7.4-4. ATLANTA APPROACHES, DISTANCE ACCURACY

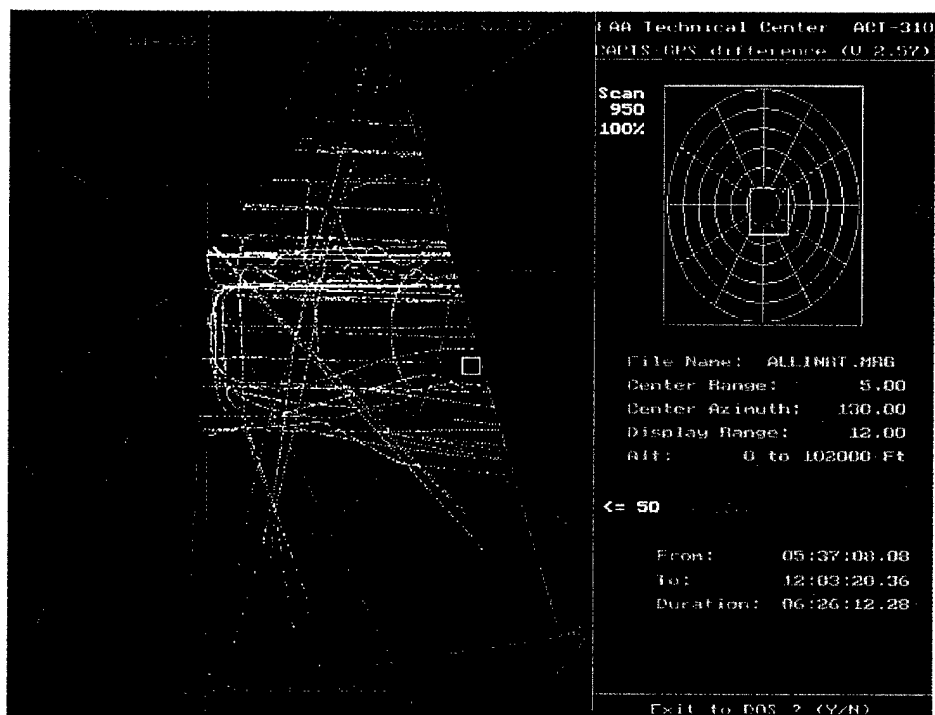


FIGURE 7.4-5. ALL OF ATLANTA AIRBORNE DATA, FILTERED FOR R/T AREA

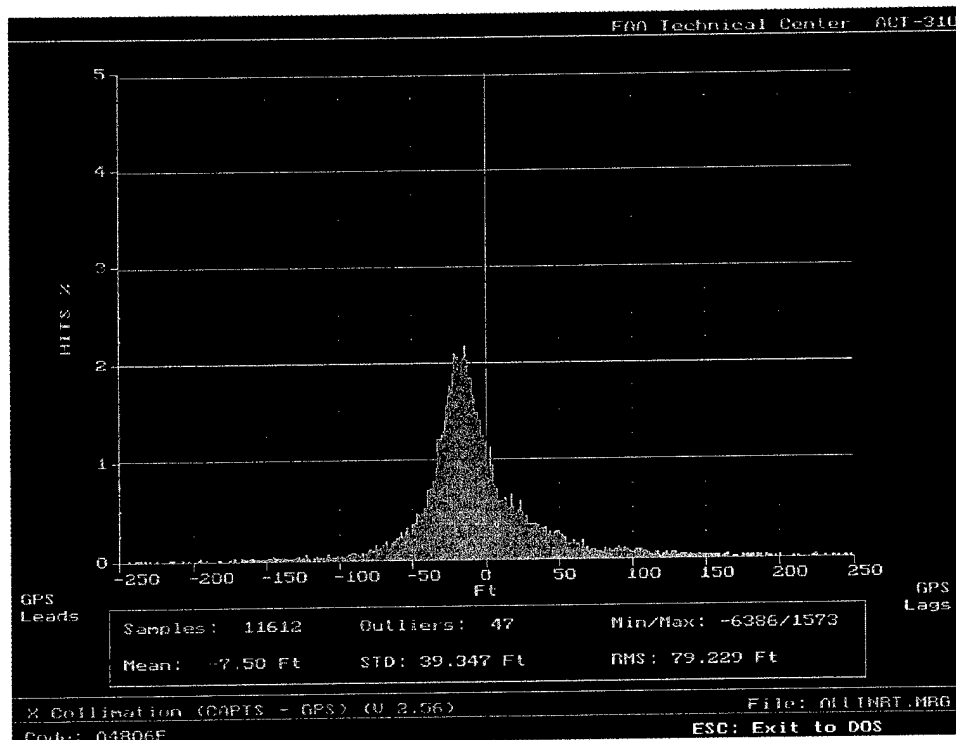


FIGURE 7.4-6. ALL OF ATLANTA AIRBORNE DATA, EAST-WEST ACCURACY

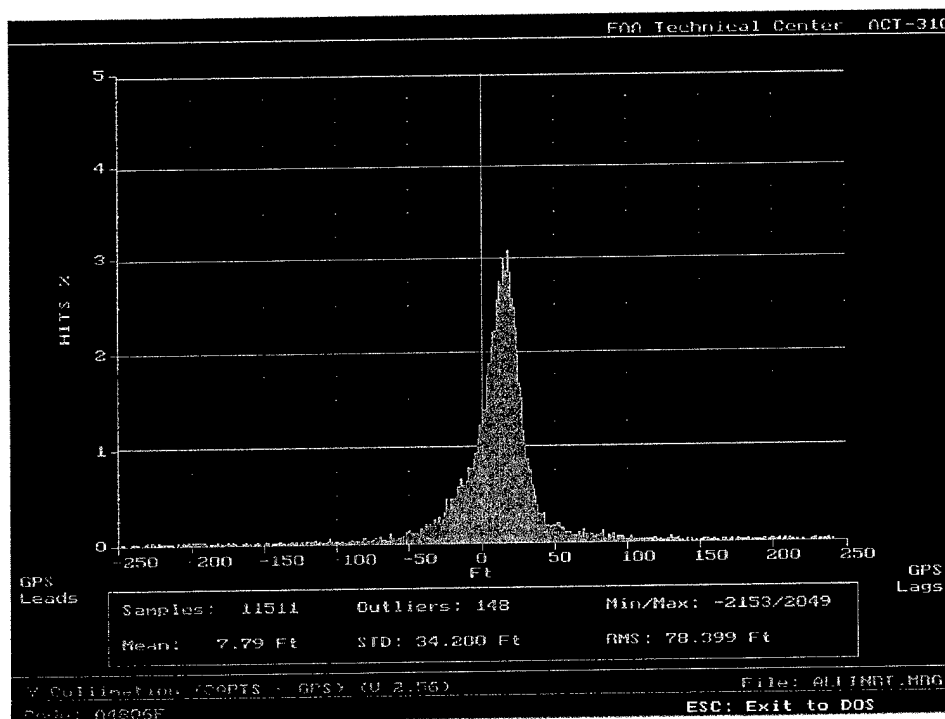


FIGURE 7.4-7. ALL OF ATLANTA AIRBORNE DATA, NORTH-SOUTH ACCURACY

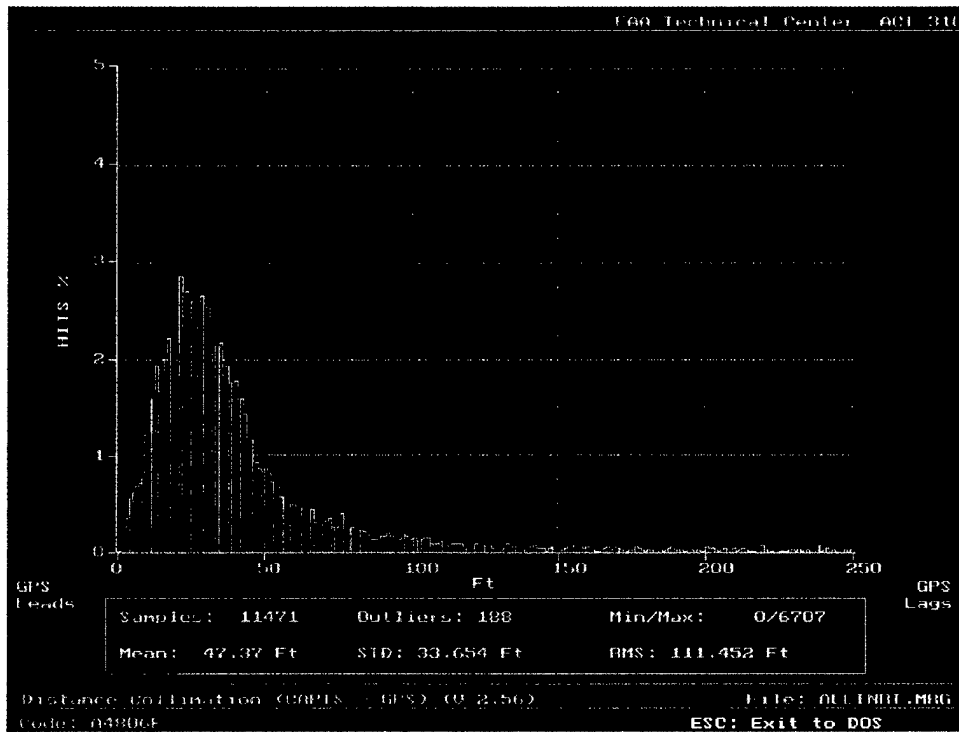


FIGURE 7.4-8. ALL OF ATLANTA AIRBORNE DATA, DISTANCE ACCURACY

In the PRM application, the CAPTS system demonstrated good positional accuracy performance. The average distance error between the CAPTS system and the differential GPS was 31.88 feet. The sample size was 4470, with a standard deviation of 22.79 feet. This yielded an RMS accuracy of 43.93 feet. The worst case distance error was 641 feet.

In the airborne surveillance application, the CAPTS system demonstrated good positional accuracy performance. The average distance error between the CAPTS system and the differential GPS was 47.37 feet. The sample size was 11471, with a standard deviation of 33.65 feet. This yielded an RMS accuracy of 111.45. The worst case distance error was 6707 feet.

8. CONCLUSIONS.

The Cooperative Area Precision Tracking System (CAPTS) is an effective Beacon system for the Airport Surface Detection Equipment Model 3 (ASDE-3) Radar System. It is sufficiently accurate to provide identification for each Mode Select Beacon System (Mode S) equipped aircraft within an ASDE-3's coverage. The system has met most of the original goals of the Cooperative Research and Development Agreement (CRDA) and has demonstrated capabilities beyond the original scope of the CRDA's Statement of Work.

Both the United Kingdom Civilian Aviation Authority (CAA) and the German CAA have leased CAPTS systems and are evaluating them for surface surveillance applications. The Federal Aviation Administration (FAA) has purchased one Receiver/Transmitter (R/T), which has been added to the five leased R/Ts in Atlanta. The National Aeronautical and Space Administration (NASA) is working with the FAA, Cardion and others to develop an integrated Surface Automation system under NASA's Terminal Automation Program (TAP). This system combines ASDE, Airport Movement Area Safety System (AMASS) and CAPTS surveillance systems with data link and avionics elements. The complete system provides a pilot with a cockpit display showing a real-time airport map complete with taxi instructions and other surface aircraft. The system underwent testing in Atlanta during 1997. The FAA has initiated a Request for Proposal (RFP) for a surface multilateration system for further evaluation at Dallas-Fort Worth (DFW) under the Airport Target Identification System (ATIDS) Program.

In comparing the electronically scanned Parallel Runway Monitor (PRM) sensor to the CAPTS system, it is necessary to establish a convention for discussing accuracy between the systems. The E-Scan sensor measures an aircraft's range and azimuth from the sensor, while the CAPTS system determines position relative to some reference point chosen in the multilateration algorithm. The E-Scan sensor has a range accuracy which is a function of receiver design which does not vary as a function of range, while its azimuth accuracy decreases with distance from the sensor. The CAPTS system has an accuracy which varies with receiver geometry, but which is relatively constant across the area with the receivers. For the Atlanta installation, the location of each R/T was chosen to favor the PRM coverage area and provide the most uniform accuracy.

The mission of the PRM is to detect aircraft traveling on parallel paths moving sideways towards one another. The PRM is always sited between the parallel runways as this makes azimuth accuracy the critical requirement of the system. As an aircraft flies an approach to a runway, the CAPTS system will track it with a uniform accuracy of 44 feet, which will exceed the E-Scan's range accuracy. For the critical requirement of azimuth accuracy, the aircraft will be tracked with the same uniform accuracy of 44 feet. The accuracy of the E-Scan sensor's at various ranges is shown in table 8-1. This means the multilateration system will track more accurately in range from the start of the approach (15 miles maximum) up to a point 7.24 miles from the threshold. From 7.24 miles to the runway threshold, the multilateration system will track less accurately than the E-Scan PRM.

TABLE 8-1. AZIMUTH ACCURACY OF E-SCAN PRM AT VARIOUS RANGES

Range (nm)	Range (feet)	Cross Range Error (feet)	Range (nm)	Range (feet)	Cross Range Error (feet)
1.0	6076	6.08	13.5	82026	82.05
1.5	9114	9.12	14.0	85064	85.09
2.0	12152	12.16	14.5	88102	88.13
2.5	15190	15.20	15.0	91140	91.17
3.0	18228	18.23	15.5	94178	94.21
3.5	21266	21.27	16.0	97216	97.25
4.0	24304	24.31	16.5	100254	100.29
4.5	27342	27.35	17.0	103292	103.33
5.0	30380	30.39	17.5	106330	106.37
5.5	33418	33.43	18.0	109368	109.40
6.0	36456	36.47	18.5	112406	112.44
6.5	39494	39.51	19.0	115444	115.48
7.0	42532	42.55	19.5	118482	118.52
7.5	45570	45.59	20.0	121520	121.56
8.0	48608	48.62	20.5	124558	124.60
8.5	51646	51.66	21.0	127596	127.64
9.0	54684	54.70	21.5	130634	130.68
9.5	57722	57.74	22.0	133672	133.72
10.0	60760	60.78	22.5	136710	136.76
10.5	63798	63.82	23.0	139748	139.79
11.0	66836	66.86	23.5	142786	142.83
11.5	69874	69.90	24.0	145824	145.87
12.0	72912	72.94	24.5	148862	148.91
12.5	75950	75.98	25.0	151900	151.95
13.0	78988	79.01			

9. RECOMMENDATIONS.

The data presented in this report effectively confirms that implementation of a multilateration system by the Federal Aviation Administration (FAA) for surface beacon surveillance should continue. There are three issues that have been raised by this technology that effect its implementation which will be addressed here. The first is an error mode that is inherent to multilateration, but which can be effectively compensated for. The second is an operational change which will be required prior to the wide-spread implementation of a system such as this. The third is developing an effective method for tracking Air Traffic Control Radar Beacon System (ATCRBS) equipped aircraft.

9.1 GARbled DIRECT RECEPTION WITH MULTIPATH ERROR MODE.

The data collected during the evaluation shows that Mode Select Beacon System (Mode S) multilateration demonstrates good overall accuracy performance, but also generates a small quantity of spurious reports with relatively high errors. These bad reports occur in locations where the error sources described in this report (Dilution of Precision (DOP) and squitter amplitude variations) do not account for the high error.

It is not possible to pinpoint the exact source of this error, based on the limited data collected. The random nature of the bad reports leads to the conclusion that the error source is environmental rather than systemic. A systemic problem, such as with the multilateration algorithms, would lead to errors occurring under similar conditions. The data does not support that conclusion. Environmental problems, such as propagation phenomenon, are a more likely cause inasmuch as the data was collected in the uncontrolled environment of a busy section of airspace.

An example of a spurious report is presented in figures 9.1-1 and 9.1-2. This was the report which generated the worst case Parallel Runway Monitor (PRM) approach data error of 641 feet. The report occurred during the zigzag approach to Runway 26L. The Cooperative Area Precision Tracking System (CAPTS) reports (in white) before and after the bad report are normal and are evenly distributed around the Global Position System (GPS) reports (in red). The position was calculated using the same triad as the six preceding positions. Other high error reports, which were examined, are similarly random in nature.

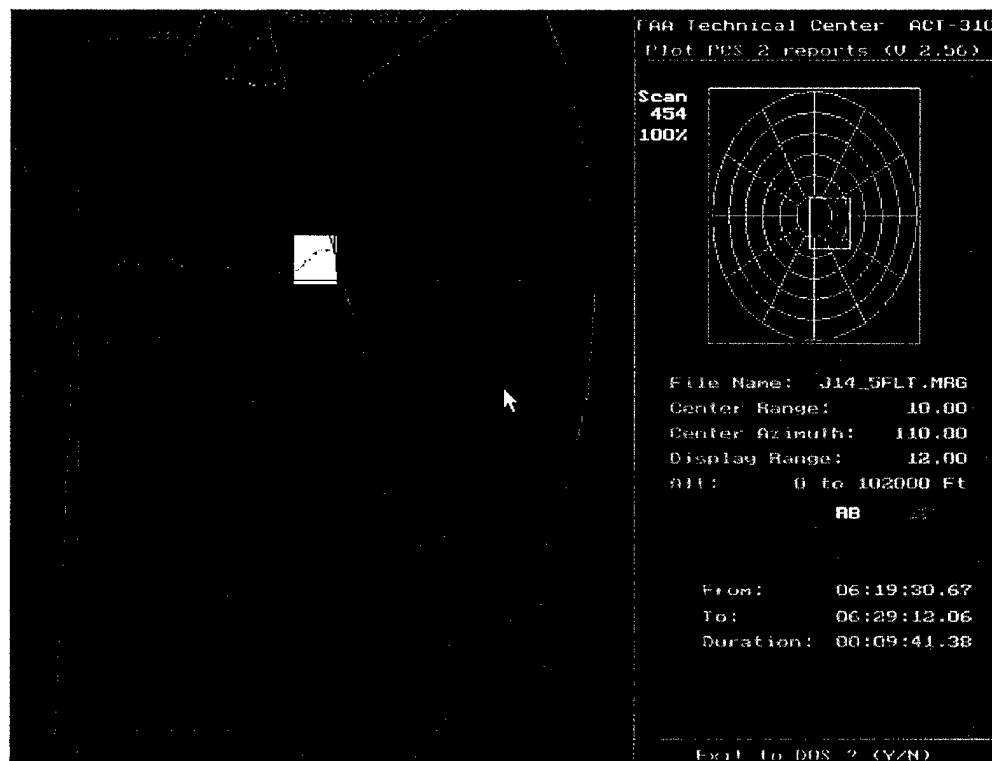


FIGURE 9.1-1. ZIGZAG APPROACH TO RUNWAY 26L

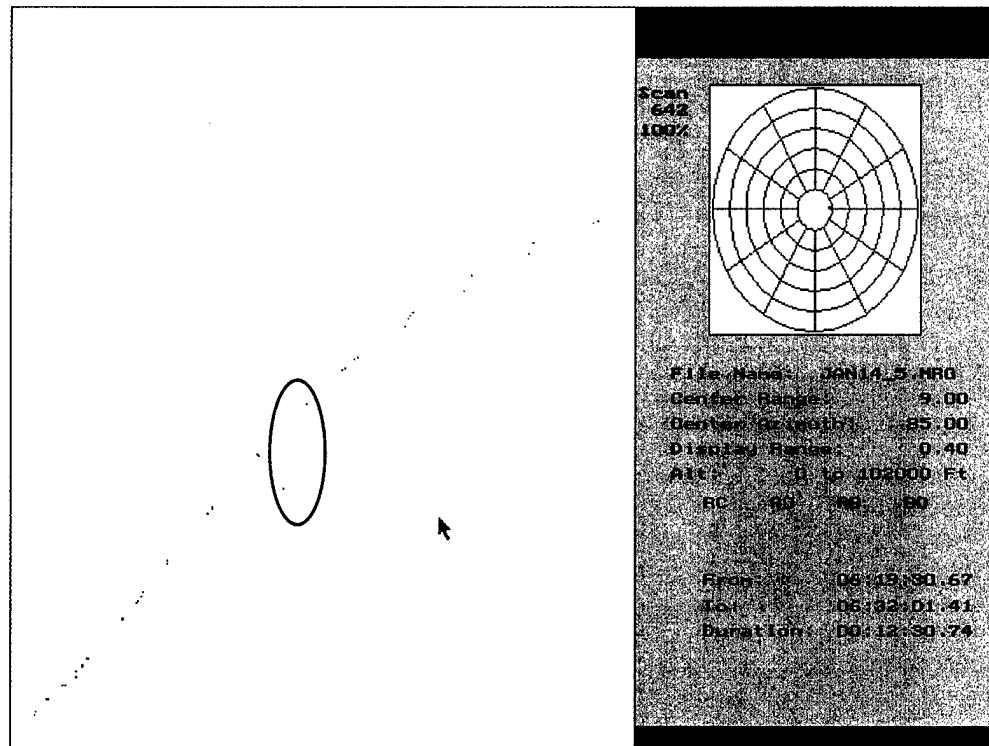


FIGURE 9.1-2. CLOSEUP OF FIGURE 9.1-1

The most likely cause of the bad reports may be the result of the combination of multipath and asynchronous garble. For this to occur requires a rare but statistically unavoidable combination where the direct reception at one Receiver/Transmitter (R/T) is garbled with some other Beacon reply. A reflected reception is then received from a multipath source, as shown in figure 9.1-3.

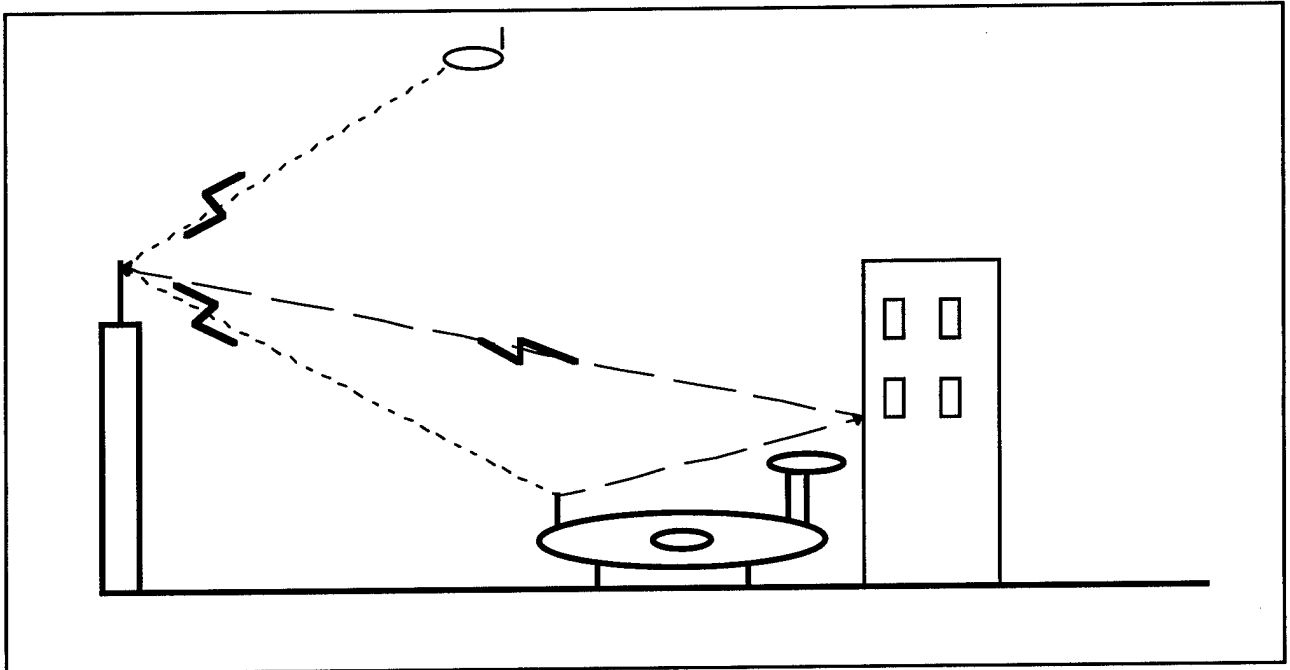


FIGURE 9.1-3. DIRECT GARBLE WITH MULTIPATH RECEPTION

The random and infrequent nature of these bad reports makes tracking a highly effective method of reducing this condition. The CAPTS system does eliminate the worst incidents of this error by “sanity checking” new targets to ensure they do not exceed acceleration parameters. Additionally, data from prior target reports are used to provide smoother tracking of targets. The sanity checking eliminates reports with the highest error but the data collected for this report demonstrates that occasionally reports, with abnormally high error, are passing the sanity checker even for stationary targets.

More processing overhead could allow the best possible accuracy and update rate by using a triad consensus processing. Cardion currently creates tables to rank the available R/T triads for each area of CAPTS coverage. A solution is calculated for the highest ranked triad which has all three R/Ts reporting. In the event of rejection of this result by the sanity checking algorithm, another solution is calculated. If the CAPTS system calculated solutions for all available triads, the remaining triads could be used to verify the validity of the initial solution. If that solution is found to widely disagree with the remaining triads, a substitute triad solution could be reported. This method could reduce both isolated high error reports and the problem related to low DOP areas of coverage.

9.2 REQUIRED CHANGE TO TRANSPONDER OPERATIONAL PROCEDURES.

Multilateration is by design a cooperative surveillance technique, and it thereby relies on the reception of some signal from the aircraft. In the case of the beacon multilateration, the signal used by the CAPTS system is typically the Mode S surface squitter (although any Mode S Downlink Format (DF) message can be used). Early in the project, it became apparent that transponders are not left operating during taxi operations. The system would receive airborne squitters during the approach, which would switch to surface squitters once the aircraft was on the runway. The aircraft would then slow on the runway and turn off the runway onto a taxiway. Not long after being on the taxiway, the target would disappear.

A pilot currently switches the aircraft transponder control head to “off” once clear of the runway after arrival. Similarly, when departing they do not switch the transponder to “operate” until cleared to depart by the controller. For a system like the CAPTS system to be effective, the aircraft transponder will need to remain in operation and provide Mode S squitters until the aircraft reaches the gate. A Mode S transponder uses the input from the aircraft’s Weight on Wheels (WOW) switch to change from the airborne mode to the surface mode. In the surface mode, the transponder no longer replies to interrogations from ATCRBS interrogators, but still provides the surface squitter used for multilateration and data link operations.

The procedure of turning off transponders was established years ago to prevent the display of symbology over the airport on the Automated Radar Tracking System (ARTS) displays. Since that time, the implementation of ARTS Auto-Drop zone software in the ARTS system, and the installation of WOW switches in most aircraft has made this procedure unnecessary. The procedure has remained in effect because there has not been a sufficient motivator to change the procedure. With current technology, a Mode S transponder left in the Surface Mode while the aircraft is on the surface would have no adverse effects on the controller’s display. It would provide tower controllers with the safety and automation benefits of knowing the call sign of surface aircraft during low visibility operations and would have only a very minor effect on the utilization of the Beacon frequencies. Since the FAA Surface Program Office is already moving to procure the Airport Target IDentification System (ATIDS), these operational changes will have to be addressed before the first system is installed.

9.3 TRACKING AIRCRAFT EQUIPPED WITH ATCRBS TRANSPONDERS.

The CAPTS system as currently implemented cannot track ATCRBS-equipped aircraft consistently. The Whisper-Shout method is used to create a single distinct reply sequence that each R/T can accurately time stamp. Once this reply sequence is created, the same multilateration method can calculate the target’s position with the same accuracy as a

Mode S-equipped aircraft. The current implementation cannot reliably generate a single reply sequence. If future advances can improve the update rate of ATCRBS targets, this method could provide good tracking of those targets.

Implementation of Whisper-Shout sequences also reduces the processing availability of the system to the point where it greatly reduces the tracking of Mode S-equipped aircraft. Cardion is currently planning to upgrade the Master Work Station (MWS) hardware from a Pentium-Based work station to a multiprocessor Reduced Instruction Set Code (RISC) work station when the FAA purchases a preproduction or production system. It is not possible to predict if this will make the implementation of ATCRBS tracking possible or practical.

The effect of not currently being able to track the ATCRBS-equipped aircraft is dependent on how the system is implemented. If CAPTS is being considered for use as a stand-alone system for tracking aircraft at an airport that currently has no surface sensors, this will have a large impact on the system usability. ATCRBS-equipped aircraft will not appear to controllers, so its use as a safety system is inadvisable, and its use as a controller aid is severely limited.

If the system is used to supplement other sensors, such as an Airport Surface Detection Equipment Model 3 (ASDE-3)/Airport Movement Area Safety System (AMASS) system, the impact is more tolerable. ATCRBS-equipped aircraft would still appear to the controller as an AMASS target. It would not be identified by an ARTS tag unless that information had been previously provided by AMASS.

10. ACRONYMS AND ABBREVIATIONS

ACY	Atlantic City International Airport
ADLP	Airborne Data Link Processor
ADS	Automatic Dependent Surveillance
AMASS	Airport Movement Area Safety System
ARSR-4	Air Route Surveillance Radar Model 4
ARTS	Automated Radar Tracking System
ASDE-3	Airport Surface Detection Equipment Model 3
ASR-9	Airport Surveillance Radar Model 9
ATC	Air Traffic Control
ATCBI-5	Air Traffic Control Beacon Interrogator Model 5
ATCRBS	Air Traffic Control Radar Beacon System
ATIDS	Airport Target IDentification System
ATL	Atlanta Hartsfield International Airport
Bd	baud
CAA	Civil Aviation Authority
CAPTS	Cooperative Area Precision Tracking System
CRDA	Cooperative Research and Development Agreement
CRO	Cooperative Research Organization
DF	Downlink Format (Mode S)
DGPS	Differentially Corrected GPS
DOP	Dilution of Precision

EARTS	Enroute Automated Radar Tracking System
FAA	Federal Aviation Administration
FMA	Final Monitor Aid
GPS	Global Positioning System
ID	Flight Number Identification
Kb	kilobaud
MHz	megahertz
MITLL	Massachusetts Institute of Technology Lincoln Laboratories
Mode S	Mode Select Beacon System
ms	millisecond
MWS	Master Work Station
NASA	National Aeronautical and Space Administration
NTZ	no-transgression zone
ns	nanosecond
RCL	Radio Communications Link
RF	Radio Frequency
RISC	Reduced Instruction Set Code
R/T	Receiver/Transmitter (CAPTS)
PC	Personal Computer
PRM	Parallel Runway Monitor
RMS	Root Mean Square $\sqrt{[1/N[\sum x_i^2]]}$

STD	Standard Deviation $\sqrt{\sum[(x_i^2 - Nx^2)/(N-1)]}$
TAP	Terminal Automation Program
TCAS	Traffic Collision Avoidance System
TDOA	Time Difference of Arrival
UF	Uplink Frequency (Mode-S)
US	United States
VAC	volts alternating current